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Performance of Hydrated Lime on the Durability of Portland Cement Concrete

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Abstract

In this work, the effect of using hydrated lime (HL) on the durability of Portland-cement (PC) concrete at 28 days was studied. A constant mix ratio of 1:2:4 (PC: sand: granite) with water/cement ratio of 0.5 was adopted. Cement was substituted with HL from 0% to 30% at intervals of 5%. Concrete specimens were cylinders of size 50mm x 100mm diameter and cubes of size 150mm. These were used to conduct compressive strength, water absorption and sulfate attack tests. Samples were allowed to cure in water for 28 days before testing. The results revealed that the more the content of HL the more water flowed through the cement paste. Best value of 5.875% water absorption was seen at 0%HL while, the largest absorption reading of 8.45% was obtained at 30%HL. Compressive strength rose as HL content increased up to 15% before it dropped. Highest compressive strength of 15.11N/mm^2 was obtained at 15% replacement giving a strength increase of about 28.26% when compared to the control strength. Cube samples subjected to sulphate attack experienced a reduction in their density after soaking for 24hours in a solution of 2.5% sodium sulphate (Na_2SO_4). In conclusion, the effect of substituting PC with HL in concrete making can improve strength and resistance to sulphate attack within 13% to 15% HL inclusion but does not improve water absorption at 28 days for mix 1:2:4 at 0.5 water/cement. So, this concrete must not be used in marine environment.

Keywords: *Water-absorption, Workability, Compressive strength, Sulphate- attack*

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1. Introduction

The significant qualities of concrete, such as its strength, fire resistance, and general longevity, makes it a globally recognized and acceptable construction material. Concrete buildings are often built with the goal of effectively withstanding the stresses placed on them during their service life as well as minimising any negative impacts brought on by the environment. However, it is important to keep in mind that concrete is known to have a low tensile strength, which could lead to the development of cracks and fissures if the manufacturing process is not adequately controlled leading to, durability issues (Husein *et al.*, 2021).

When referring to a particular substance, the term "durability" refers to the manufacturer's guarantee that the material will maintain its mechanical, aesthetic, and functional qualities for the duration of the estimated useful life. Durability in the context of structural design means that the structure's surface can be used for the anticipated amount of time without the need for extra security measures or maintenance work (Maj *et al.*, 2020). According to Bonic *et al.* (2015), problems with concrete's durability are frequently caused by aggregate expansion, carbonation, concrete degradation, salt weathering, or leaching inside the concrete matrix. These actions cause the relative humidity inside the concrete to be higher than it would be under typical conditions.

The durability of concrete structures that are subjected to severe environmental conditions has consistently been a subject of great apprehension for the construction sector. For instance, the likelihood of reinforcement corrosion escalates in structures that are exposed to elevated levels of chloride and sulphate salts, as well as heightened temperatures and humidity (Omar *et al.*, 2022). The ramifications of concrete with high humidity levels are manifold and encompass various factors. These include the proliferation of bacteria and mold on the concrete's surface, which ultimately diminishes its compressive strength. Moreover, heightened humidity levels can affect the pH level of the concrete, resulting in an acidic nature. In addition, any coating or adhesive material that is applied to the concrete surface may struggle to adhere properly. Prolonged exposure to harmful chemicals can lead to detrimental reactions with the concrete, particularly over a significant period of time.

The negative occurrences associated with durability issues usually amount to concrete structures' owners and other stakeholders losing a significant amount of money to the maintenance and repair of damaged concrete structures. Therefore, to safeguard against these detrimental exposure conditions, and unwanted cost, it is imperative to manufacture concrete of exceptional quality and best suited to the area in which the structure will be located (Bonic *et al.*, 2015). In this study, Portland cement was partially substituted with hydrated lime, and the effectiveness of this substitution on the 28-day-old concrete's durability was tracked.

Lime cement concrete has been extensively investigated due to its durability. Seyed *et al*. (2021) studied the *permeability of concrete containing limestone powder in marine curing conditions.* They partially replaced Portland cement with limestone powder and conducted water absorption, rapid chloride penetration and water penetration tests on samples cured in normal water and sea water at 7, 28 and 90 days respectively. In their findings, they observed that chloride permeability, water absorption and penetration all increased with higher limestone content in concrete. However, samples containing 5% and 15% limestone experienced less chloride penetration for seawater condition when compared to the control samples. At 30% limestone content, penetration depths increased for both curing conditions. The compressive strengths of all samples cured in seawater reduced in comparison to their controls.

The use of hydrated lime (HL) was explored by Omar *et al*. (2022) as a means of activating a natural pozzolan (NP) in the context of concrete production, acting as a replacement for the conventional ordinary portland cement (OPC). The researchers explored three distinct mixtures, namely: 100% OPC; 80% OPC:20% NP; and 73% OPC:20% NP:7% HL. Overall, it was duly observed that the incorporation of HL resulted in an enhanced performance of the NP, characterized by its efficacy as a pozzolan material in the production of concrete. However, this inclusion also led to a modest increase in the concrete's vulnerability to sulphate attack. The activation of the NP through HL yielded positive outcomes in terms of water permeability, chloride diffusion, as well as the concrete's resistance against carbonation and salt weathering. Despite the partial replacement of OPC with NP, the concrete exhibited an improvement in both its initial and final strength, effectively compensating for the strength loss associated with this partial substitution.

Gao *et al*. (2021) carried out an investigation to examine the influence of limestone powder on the thaumasite form of sulphate attack in materials made of cement. The outcomes of their investigation showed that the existence of limestone powder varying from 5% to 10% can effectively stabilise ettringite and boost the formation of gypsum, thus improving the resistance of the material against sulphate attack. However, the occurrence of sulphate attack was accelerated when the limestone powder content was within the range of 15% to 30%. This occurrence can be attributed to the rapid decrease in the pH value and the amount of calcium oxide (CaO), while simultaneously increasing the amount of sulphate oxide (SO_3) beyond the 10% threshold of limestone powder. Consequently, the speedy sulphate attack presented a significant drawback. In addition, they observed that an excessive limestone powder content of up to 45% slowed down the effect of sulphate attack. This was due to the formation of hydrated calcium carbon- aluminate when more limestone powder combined with tricalcium aluminate (C_3A). This study seeks to investigate the durability effect of using only hydrated lime as a partial substitute for Portland cement in concrete production.

2. Materials and methods

2.1 Materials

The major materials used for the production of the concrete samples adopted for the experimental study include: Hydrated lime (HL) Portland cement (PC), sand from the river (S) and crushed granite (CG). Potable water available from the structural laboratory of the Department of Civil Engineering, Federal University of Technology, Owerri, Imo State was taken as the mixing water. The HL was acquired from Okpella in Edo State of Nigeria and by the use of the X-Ray Fluorescence (XRF) test, its chemical composition was determined. PC was obtained from a local market close to the location of the laboratory. The Dangote Portland cement brand of 42.3R was used for the study. This cement is known to satisfy the requirements of NIS 444-1 (2003). Fine aggregate was sourced from the Otamiri river while crushed granite was obtained from

Okigwe in Imo State Nigeria.

2.2 Methods

Various experimental works were done on the materials for producing the concrete as well as the fresh and hardened concrete. They include:

a. The chemical property test on the HL in accordance with ASTM C25 (2019)
b. Grain size distribution test according to ASTM D6913 (2017)
c. Bulk density test on the aggregates according to ASTM C29 (2023)
e. Specific gravity test on the aggregates in accordance with ASTM D 854 (2014)
d. Slump test on the fresh concrete according to BS EN 12350-2 (2019)
f. Water absorption test according to BS 1881-122 (2011)
g. Compressive strength test according to BS EN 12390-3 (2019)
h. Sulphate attack test in accordance with ASTM C642 (2021)

1.2.1 Concrete mix proportioning

A continuous mix ratio of 1:2:4 (PC:SAND:GRANITE) at a water-cement ratio of 0.5 was adopted for the investigation, and the proportion of PC was replaced by HL at percentages of 0% (control), 10%, 15%, 20%, 25%, and 30%, respectively. Two different concrete samples were produced. They were the 50mm x 100mm cylindrical samples used for durability studies and the 150mm cubic samples adopted to measure the compressive strength of the concrete. A total of 48 cylinders and 36 cubes were made. The mix proportions for fabricating the concrete samples are presented in Tables 1 and 2.

Table 1: Proportion of mix for concrete cylinders

		Mix ratio					Proportion of mix for one cylindrical sample (Kg)				
S/No	**Mix No**	**PC**	**HL**	**W/C**	**S**	**CG**	**PC**	**HL**	**Water**	**S**	**CG**
1	N1	1.00	0	0.50	2	4	0.143	0.000	0.072	0.286	0.57
2	N2	0.90	0.10	0.50	2	4	0.129	0.014	0.072	0.286	0.57
3	N3	0.85	0.15	0.50	2	4	0.121	0.021	0.072	0.286	0.57
4	N4	0.80	0.20	0.50	2	4	0.114	0.029	0.072	0.286	0.57
5	N5	0.75	0.25	0.50	2	4	0.107	0.036	0.072	0.286	0.57
6	N6	0.70	0.30	0.50	2	4	0.100	0.043	0.072	0.286	0.57

Table 2: Proportion of mix for concrete cubes

		Mix ratio					Proportion of one cube sample (Kg)				
S/No.	**Mix No**	**PC**	**HL**	**W/C**	**S**	**CG**	**PC**	**HL**	**Water**	**S**	**CG**
1.	N1	1.00	0	0.50	2	4	1.286	0.000	0.643	2.571	5.143
2	N2	0.90	0.10	0.50	2.	4	1.157	0.129	0.643	2.571	5.143
3	N3	0.85	0.15	0.50	2	4	1.093	0.193	0.643	2.571	5.143
4	N4	0.80	0.20	0.50	2	4	1.029	0.257	0.643	2.571	5.143
5	N5	0.75	0.25	0.50	2	4	0.964	0.322	0.643	2.571	5.143
6	N6	0.70	0.30	0.50	2	4	0.900	0.386	0.643	2.571	5.143

3. Results and discussion

3.1 Chemical composition of hydrated Lime (HL)

The result of the chemical property test on the HL is presented in Table 3. It can be observed that the summation of the calcium oxide and magnesium oxide contents of the HL gave a value of about 56%. This was far less than the 95% or more stipulated by the ASTM C207 (2018) for HL used in masonry works. Content of potassium and magnesium oxides were 35.43% and 10.39% respectively.

Table 3: Oxides of hydrated lime

S/No.	Oxides	Percentage
1.	Calcium oxide	45.52
2.	Silicon oxide	0.37
3.	Iron oxide	0.05
4.	Aluminum oxide	2.91
5.	Magnesium oxide	10.39
6.	Sodium oxide	0.51
7.	Potassium oxide	35.43
8.	Phosphorus oxide	3.84

3.2 Grain size distribution of aggregates

The result of this test carried out on the granite chippings and sand sourced from the river showed that coefficient of uniformity (Cu) and coefficient of curvature (Cc) for the granite were 2.19 and 2.02. Similarly, Cu and Cc for the sand were 4.375 and 0.56. These two aggregates were poorly graded since they did not satisfy the conditions of the unified soil classification system (ASTM D2487, 2017) that says that an aggregate is well graded when Cu>5 and 1<Cc<3.

3.3 Slump test on fresh concrete

The results of the slump test as obtained from the study is presented in Fig 1. The addition of HL in the concrete mix greatly increased the consistency of the fresh mix. With more amount of HL, the workability of the concrete improved.

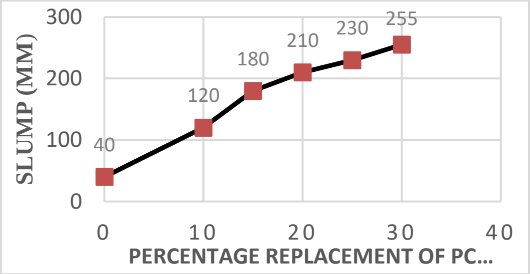

Fig 1: Slump (mm) vs % replacement 0f PC with HL.

3.4 Bulk density of aggregates

The bulk densities of the fine and coarse aggregates used for this work were obtained to be 1603.083kg/m^3 and 1384.4809kg/m^3 accordingly. This means that the aggerates are normal weight in nature and can be used to produce normal weight concrete (ASTM C29, 2023)

3.5 Specific gravity of aggregates

The specific gravity of aggregate measures the quality of the material. Aggregates with low specific gravity are usually weaker than those with higher specific gravity. For construction purposes, specific gravity of aggregate should range from 2.5 to 3 with an average of about 2.68 (ASTM D854, 2014). In this study, the specific gravity for sand and granite obtained were 1.615 and 1.65 respectively. This means that the aggregates can be classified as low strength.

3.6 Water absorption test on concrete

Table 4 and Fig 2 show the results of the water absorption test conducted on the cylindrical concrete samples.

Water absorption increased with increase in the content of HL. A slight rise of about 0.45% was achieved between 15% and 20%. Lowest value was recorded at 0% addition of HL while maximum was seen at 30% addition. So, the more the content of HL in the mix, the higher the rate at which water was assimilated by the concrete. This means that hydrated lime in concrete has great affinity for water. In conclusion, the absorption property of the concrete for all percentage replacement of PC with HL were far higher than the minimum 3% allowed by the maritime code (BS 6349-1, 2000). Therefore. this type of concrete cannot be used in marine environment.

Table 4: Water absorption test results of HL-PC concrete

S/N.	Sample no.	Duplicate	% replacement	W_i Initial weight (kg)	W_f Final weight (kg)	24 hours water absorption $(\frac{wf-wi}{wi})*$ 100 (%)	Average water absorption (%)
1.	S1	a	0	971.35	1035.46	6.6	5.875
		b		1099.04	1179.11	7.29	
		c		937.94	982.62	4.76	
		d		1105.56	1159.23	4.85	
2.	S2	a	10	1052.24	1106.04	5.11	6.178
		b		1086.40	1160.84	6.85	
		c		1098.45	1176.49	7.10	
		d		922.14	974.23	5.65	
3.	S3	a	15	915.6	982.68	7.33	7.28
		b		1126.81	1190.02	5.61	
		c		1091.35	1179.23	8.05	
		d		909.75	983.69	8.13	
4.	S4	a	20	927.15	1002.03	8.076	7.313
		b		1106.23	1193.76	7.912	
		c		1082.47	1144.69	5.747	
		d		928.72	998.52	7.516	
5.	S5	a	25	899.52	954.62	7.656	7.835
		b		1084.18	1146.19	8.134	
		c		1092.83	1151.51	7.452	
		d		933.15	986.09	8.098	
6.	S6	a	30	906.99	989.49	9.096	8.45
		b		907.11	989.36	9.067	
		c		1092.16	1187.12	8.695	
		d		1117.48	1195.04	6.9401	

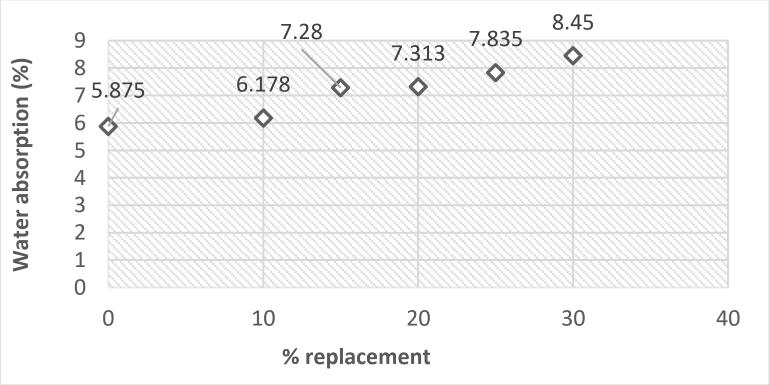

Fig 2: Water absorption (%) vs % replacement of PC with HL

3.7 Sulphate attack result on concrete

Sulphate attack on the concrete was measured by considering the density of the concrete before and after it was submerged in a solution of sodium tetraoxosulphate IV (Na_2SO_4) for 28 days. Results obtained are presented in Table 5. Overview, it can be seen that while the quantity of HL in the concrete increased, the density kept dropping in the presence of Na_2SO_4. But at 10% HL content, the density of the specimen was really not affected. This finding is in line with the observation made by Gao *et al.* (2021) that at 10% limestone inclusion in a cement-based material, sulphate attack did not occur due to the content of limestone powder that can boost the formation of gypsum and help resist the attack. A minimal decrease in density of 1.98% was observed at 15% HL content. This trend progressed as the content of HL increased. Maximum reduction of 4.31% was recorded at 30% HL inclusion. Addition of more and more hydrated lime can lead to a rapid decrease in the pH and the content of CaO and a rapid increase in the content of SO_3 and this accelerates the sulphate attack (Gao *et al*., 2021). Therefore, the optimal percentage substitution of PC with HL to resist sulphate attack on concrete is at 10%.

Table 5: Density of concrete before and after exposure to sulfate attac**k**

Sample No.	Before exposure (kg/m^3)	After exposure (kg/m^3)	% difference
S1	2429.63	2370.37	2.439054506
S2	2391.11	2405.93	-0.619795827
S3	2539.26	2488.89	1.98364878
S4	2610.37	2539.26	2.724134893
S5	2459.26	2380.44	3.205029155
S6	2477.04	2370.37	4.306349514

3.8 Compressive strength result

Values generated from the compressive strength test conducted on the cube samples are shown in Fig. 3. As the content of HL increase from 0% to 15%, compressive strength rose by about 28.27%. However, between 15% and 20% there was a major drop in strength of about 30.91%. This strength gradually kept decreasing until the 30% HL substitution was reached. Therefore, it can be seen that optimum inclusion of HL as substitute for PC with respect to strength is at 15% and concrete produced were low strength in nature. This could be due to the type of HL used for the study. The quantity of the sum of CaO and MgO did not reach standard content of 95% as stipulated by ASTM C207 (2018). So, HL used for the study was not a high calcium HL or dolomite HL which are known to be very good for construction purposes. It contained more than 8% Magnesium oxide which aided in reducing the strength of the concrete (Liu and Li, 2005). Also, compared to the strength of the calcium-silicate-hydrate (C-S-H) gel that is formed during PC hydration, the strength contribution of calcium hydroxide is lower due to lower surface area (Mehta and Monteiro, 2006). The HL adopted was not the high calcium type required for masonry work.

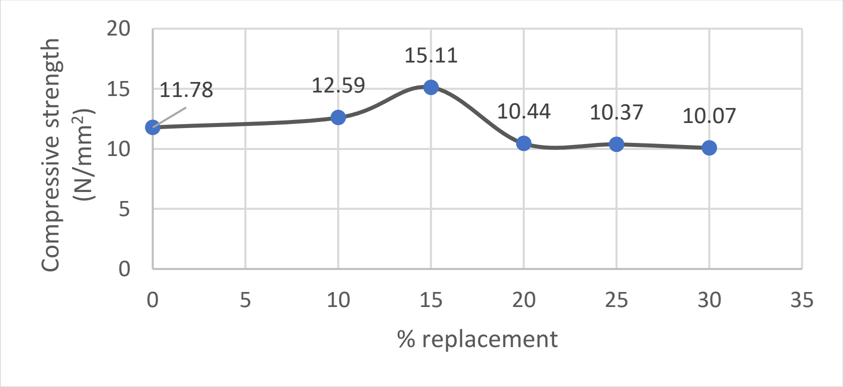

Fig 3: Compressive strength (N/mm^2) vs. % replacement of PC with HL.

3.9 Relationship between compressive strength and water absorption.

The relationship between the water-absorption and the compressive strength of the concrete is illustrated in Fig. 4. This relationship shows that although the affinity for water by the concrete rose from 5.875% at 0%HL content to 7.238% at 15%HL, the strength of the concrete kept increasing. This could be due to the fact that some quantity of HL in the mixes were used up in reacting with silicon oxide from the PC thereby generating more of the strength gaining C-S-H gel in the cement matrix despite the presence of additional void spaces caused by HL attraction for water. However, after this benchmark, strength of the concrete dropped drastically as the amount of HL content increased. This happened because the quantity of HL in the mixes were more than required. After the combination of some HL with silicon oxide from the PC, excess HL was still left unused in the cement matrix and its low surface area led to strength loss. Also, this excess HL in the matrix attracts so much water thereby introducing more void spaces to the matrix.

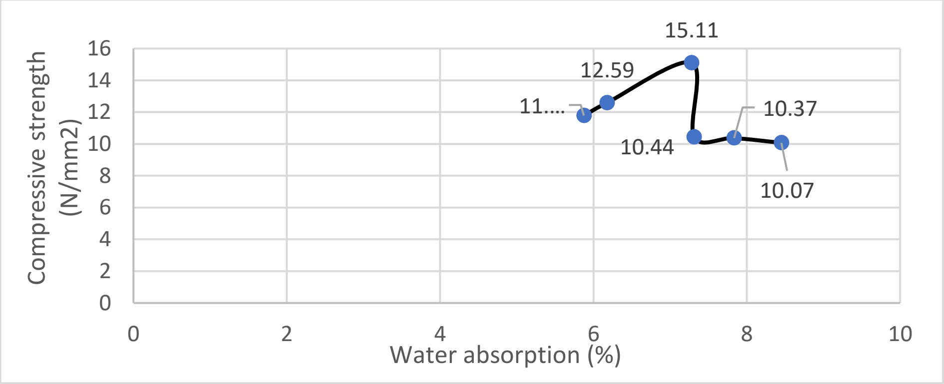

Fig 4: Compressive strength (N/mm^2) vs % water absorption

4. Conclusion

In this study, the durability of PC concrete admixed with HL was carried out. HL was used as a substitute for PC at 10%, 15%, 20% 25%, and 30% by weight of the cement correspondingly. The workability of the concrete was greatly improved as the HL content was introduced into the mix. Therefore, the HL can be used as a plasticizer in some concrete works. In order to apply HL in producing concrete with some degree of sulphate resistance, 10% to 15% HL can be used to replace PC in the concrete mix. Percentages lower or higher than this range will develop a negative effect. Similarly, compressive strength improvement of the concrete can be achieved between 5% to 15% PC replacement with HL with the optimum at 15%. HL-PC concrete must not be applied when carrying out marine construction since the HL has shown to have so much attraction for water. Its use in marine environment will cause quick deterioration of the structures since the concrete will always be in the presence of water all the time. In conclusion, producing HL-PC concrete using mix 1:2:4 at 0.5 water-cement ratio with poorly graded aggregates having specific gravity between 1.6 – 1.65 will generate low strength concrete and this cannot be used for structural purposes.

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