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Performance evaluation of interlocking paving units in aggressive environments

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KEYWORDS

Interlocking paving units;
Compressive strength;
Water absorption;
Abrasion resistance;
Aggressive environments;
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Environmental conditions

Abstract This study evaluates the performance of interlocking paving when exposed to aggressive environments. Durability of paving units is an essential property as it determines its capability of withstanding the different conditions to which it is expected to be exposed to- Chemical, physical, and mechanical causes can result in lack of durability. Chemical cause can arise from attack by chlorides, physical cause may be due to exposure to high temperature variations, while mechanical causes are usually associated with abrasion. Experiments were carried out to determine product compressive strength, water absorption, and abrasion resistance according to both Egyptian Standard Specifications (ESS) and American Society for Testing and Materials (ASTM). An interlocking paving mix was chosen and exposed to various aggressive media for a duration of 2 months after being cured for 28 days. The aggressive environments were as follows: 1% HCl, 5% HCl solution (to simulate acid attack resistance), dry and wet cycles, as well as, air (room temperature) and dry cycles (to simulate different environmental conditions). The tested products were also X-rayed to investigate the mineralogical analysis. The following was concluded. The four aggressive media increased compressive strength when compared to the control mix. Also, they resulted in reducing water absorption percentages and met the criteria for water absorption concerning heavy duty according to ESS. Samples which were exposed to the four aggressive environments conditions did not satisfy both criteria of ESS and ASTM pertaining abrasion.

Introduction

Interlocking paving units have been recently included in the Egyptian Standard Specifications. The main constituent materials of paving units are cement, sand, crushed stone, and water. This study, evaluates the performance of paving units in aggressive environments.

Durability is an important engineering property of concrete, which determines the service life of concrete structures significantly. Due to the interactions of concrete with external influences, the mechanical and physical properties of

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concrete may be threatened. Among the threatening factors are freezing and thawing, abrasion, corrosion of steel, as well as chemical attack which may also deteriorate concrete with time.

This study, evaluates the performance of paving units in hydrochloric acid which is the aqueous solution of hydrogen chloride gas (HCl). It is a strong acid, a major component of gastric acid and widely used in industry.

The action of HCl on cement hydration products, in particular Ca $(OH)_2$ and the resulting products are presented in the following chemical equation:

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$$

From the equation it can be seen that, consumption of $Ca(OH)_2$ results in the formation of salts of $CaCl_2$. By the help of water, these soluble salts may easily be transported.

The rate of acid attack can be mainly related to the concentration of the solution.

Portland cement concrete hydration products are alkaline and when exposed for a certain period of time to acid attack, they show signs of wear [1].

Pavers have several applications that can be categorized into heavy duty, medium duty, and light duty. Examples of heavy duty are ports, city streets, and factory yards. Residential streets, pedestrian crossings, and car parks are considered medium duty while walkways, bicycle paths, and garden footpaths are light duty [2].

Haynes et al. studied the effect of physical attack to which concrete might be exposed to in soils containing sodium sulfate. To promote physical attack, a concrete mixture was made with a low C3A, ASTM Type II Portland cement, using a w/c ratio of 0.65. After curing, cylindrical concrete specimens were partially submerged in a 5% sodium sulfate solution for periods up to 3.1 years. Tests were conducted under temperature and humidity cycles simulating various ambient conditions, one of which promoted alternate cycles of conversion between Na_2SO_4 and $Na_2SO_4 \cdot 10H_2O$. Overall, the results showed that concrete scaling occurred at evaporation surfaces directly above the solution level, and significant scaling occurred when concrete was subjected to numerous cycles of Na_2SO_4 – $Na_2SO_4 \cdot 10H_2O$ conversion [3].

Aguiar et al. studied the efficiency of surface treatment in acting as a barrier between the environment and the concrete, preventing or retarding the entry of harmful substances and cutting off the transportation path into concrete. This work was intended to contribute to a better understanding of the performance of protected concrete in chemically aggressive environments, by presenting results of ion diffusion and resistance to aggressive solutions of several hydrophobic agents and coatings used to protect concrete. Three different types of surface protections were tested: silicone hydrophobic agent, acrylic and epoxy coatings. The obtained results indicate that the overall performance of epoxy resin was better than the other selected types of protections [4].

Chemical attack poses a serious problem for concrete structures in severe environments. This investigation carried out by Heghes et al. deals with exposure of high strength/high performance concrete to sulfate attack in a controlled environment. Experimental tests consisted of measuring the compressive strength, tensile strength, and modulus of elasticity after 3 years of exposure to corrosive conditions consisting of chemical solutions containing 1% $(NH_4)_2SO_4$ and 2% $(NH_4)_2SO_4$ [5].

Murthi et al. investigated the acid resistance of ternary blended concrete immersed up to 32 weeks in sulfuric acid and hydrochloric acid solutions. The results were compared with those of the control and binary blended concrete. The variable factors considered in this study were concrete grades (M_{20}, M_{30}, and M_{40}) and curing periods (28 and 90 days) of the concrete specimens. The parameter investigated was the time in days taken to cause 10% mass loss and strength deterioration factor of fully immersed concrete specimen in a 5% H_2SO_4 and 5% HCl solutions. The investigation indicated that the ternary blended concrete performed better acid resistance than the ordinary plain concrete and binary blended concrete [6].

Xiong et al. carried out an exploratory test to etch concrete substrate by using 1% and 2% hydrochloric acid solutions. The exploratory test results showed that 1% and 2% Hcl solutions had little influence on splitting bond strength between the concrete substrate and the repair material. Hydrochloric acid solutions of 5%, 7%, and 10%, therefore, were chosen for formal testing. It was concluded that the bond strength of the specimens etched with 5% consistency of HCl solution was 25.5%, 6.1% and 15.5% higher than those etched with 0%, 7% and 10% HCl acid solutions. [7].

Materials and methods

Cement

The cement used was ordinary Portland cement CEM I 52,5N in accordance to ESS 4756-1/2007. Properties of ordinary Portland cement are shown in Table 1, and the chemical composition is shown in Table 2.

Fine aggregates (sand, and marble rubble)

Siliceous sand was used in this research program. The sieve analysis is shown in Fig. 1. Table 3 gives the physical properties of fine aggregates, while Table 4 shows the chemical composition of marble powder.

Coarse aggregates (crushed stone)

Crushed limestone was used in this research. Fig. 2 shows the sieve analysis of crushed limestone, as supplied. Table 5 shows the physical properties of coarse aggregates. The chemical analysis of crushed limestone is given in Table 6.

Preparation of aggressive media

(A) 1% of HCl, pH = 2.088 and concentration = 0.027 mol.
(B) 5% HCl, pH = 1.54, and concentration = 1.37 mol.

A strong acid having a high degree of dissociation (e.g. hydrochloric acid, nitric acid) may achieve very low values of pH, due to relatively small quantities of acid in the solution. The weak acids owing to their low dissociation degree, achieve higher PH values. The given relationships should be taken into consideration when the rate of acidic attack is the subject of interest [8].

Table 1 Ordinary Portland cement properties according to ESS 4756-1/2007.

Property	Description	Test results	Standard requirements
Setting time (min)	Initial	150 min	Not less than 45 min
	Final	195 min	–
Soundness (mm)		1	Not more than 10
Compressive strength (MPa)	2 days	23.5	Not less than 20
	28 days	55.2	Not less than 52.5

Table 2 Chemical composition of ordinary Portland cement.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	P_2O_5	L.O.I.	Total
19.95	4.91	3.45	62.35	0.72	0.4	0.272	3.19	-	-	4.72	99.96

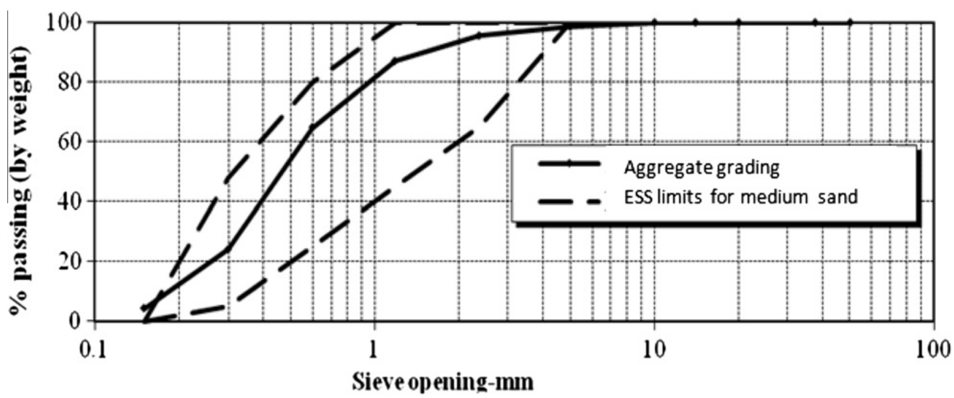


Fig. 1 Sieve analysis of sand.

Table 3 Fine aggregates physical properties.

Sand	Property
2.56	Specific weight
1.52	Volumetric weight (tons/m^3)

Table 4 Chemical composition of marble powder.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	P_2O_5	L.O.I.	Total
1.31	0.19	0.19	54.18	0.02	0.04	0.09	1.3	0.02	0.12	41.99	99.45

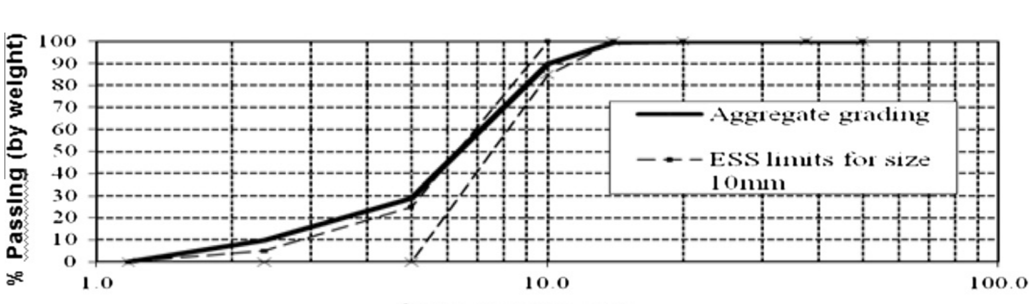


Fig. 2 Sieve analysis of crushed limestone.

Table 5 Coarse aggregate physical properties.

Acceptance limits	Crushed stone	Property
–	2.76	Specific gravity
–	1.62	Volumetric weight (tons/m^3)
Not more than 2.5%[a]	0.55%	Absorption percentage
Not more than 3% by weight[b]	0.2%	Clay and other fine materials (%)
Not more than 30%[b]	25%	Impact value (%)

[a] According to the Egyptian code of practice issued 2001.
[b] According to the Egyptian Standard Specifications 1109/2002.

Table 6 Chemical analysis of crushed limestone.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	P_2O_5	L.O.I.	Total
0.92	0.18	0.09	55.26	0.14	0.04	0.08	2.03	0.01	0.05	40.9	99.7

Table 7 Interlocking paving units′ mixture proportions and aggressive environments.

Constituents materials (kg/m^3)	Cement	Sand	Crushed stone	Marble powder	Water
Facing layer	150	450	–	–	55
Backing layer	600	1125	675	450	180
Aggressive environments	Acid solution	Immersed for 5 days in 1% HCl and dried in oven for 8 h (one cycle) Immersed for 5 days in 5% HCl and dried in oven for 8 h (one cycle)			
	Environmental condition (1)	Air and dry (kept at room temp and dried in oven at 70 °C for 6 h) (one cycle)			
	Environmental condition (2)	Wet and dry (immersed in tap water for 5 days and dried in oven at 70 °C for 8 h) (one cycle)			

Interlocking mixture proportions

The control mix design for the manufactured product was selected from previous research work [9], and tested at age 28 days (as specified by the Egyptian Standard Specification) and at age 90 days to be able to compare its results with the specimens which were exposed to the various aggressive media. For 28 days after casting, all specimens were sprayed twice daily. The control specimens were stored at room temperature after age 28 days until tested at age 90 days without being sprayed. Concrete mixture proportions and aggressive environments are given in Table 7. The product consisted of two layers. The top layer (facing layer) was approximately 8 mm → 10 mm thick while the bottom layer (backing layer) was about 70 mm thick. The demoulding ability is an essential criterion for manufacturing paving units. The water contents of the paving units were adjusted based on this criterion. The (w/c) ratio was adjusted for each mix to maintain an almost zero slump. Crushed stone was not washed prior to mixing. The testing plan is shown in Table 8.

Table 8 Interlocking paving units testing plan.

Tests carried out on products	Testing method	Number of blocks
Compressive strength	ESS 4382 ASTM C 140	5
Water absorption percentage	ESS 4382 ASTM C 140	5
Abrasion resistance	ESS 4382 ASTM C 418	3

The specimens were exposed to aggressive environments after being cured for 28 days. The paving units were exposed to four aggressive environmental conditions. The first two conditions were as follows: the specimens were exposed to alternate cycles of immersion in 1% HCl solution for 5 days and then placed in oven at 70 °C for 8 h. The second condition was similar to the first except that the specimens were immersed in 5% HCl solution. The first and second conditions were carried out for 8 weeks. The HCl solutions were tested every 2 weeks to ensure the stability of the PH. The third condition (air & dry) was a simulation of high variation in temperature condition. In other words, the specimens were maintained at room temperature for 19 h and dried in oven at 70 °C for 6 h (daily cycle). This cycle was carried out 5 days a week for 8 weeks. The final condition will be referred to as wet and dry condition. This condition comprised alternate cycle of immersing the specimens in tap water for 5 days and drying them in the oven for 8 h. This cycle was also conducted for 8 weeks. Wetting and drying was used as an accelerated test method to simulate outdoor environmental conditions.

Results and discussions

Compressive strength

The compressive strength was tested for the control specimens (at ages 28 and 90 days, respectively) as well as for the

Table 9 Interlocking paving units physical properties according to ESS 4382–1/2004 [10].

Duty Property	Heavy duty	Medium duty	Normal duty
Compressive Strength (N/mm^2)	Avg. compressive strength of the samples shall not be less than 55 N/mm^2 with no individual unit less than 50 N/mm^2	Avg. compressive strength of the test samples shall not be less than 35 N/mm^2 with no individual unit less than 30 N/mm^2	Avg. compression strength of the test samples shall not be less than 30 N/mm^2 with no individual unit less than 25 N/mm^2
Absorption percentage	The avg. absorption of the test samples shall not be greater than 5% with no individual unit greater than 7%	The avg. absorption of the test samples shall not be greater than 6% with no individual unit greater than 8%	The avg. absorption of the test samples shall not be greater than 8% with no individual unit greater than 10%
Abrasion resistance	Specimens shall not have a greater volume loss than 15 cm^3/50 cm^2. The avg. thickness loss shall not exceed 3 mm		

Table 10 Test results of properties of paving units.

Mixes	Average product comp. strength (N/mm^2)	Avg. product absorption percentage	Abrasion	
			Volume loss (cm^3/50 cm^2)	Avg. thickness loss (mm)
Control (28 days)	41[a] 32.1[b]	6.42[a] 7.0[b]	13.5	3.4
(90 days)	49[a] 45.7[b]	4.0[a] 4.7[b]	12	3.2
1% HCl	47.3[a]	2.1[a]	30.81	8.0
(90 days)	39.6[b]	2.44[b]		
5% HCl	57.3[a]	1.55[a]	24.53	7.0
(90 days)	48.0[b]	2.26[b]		
Air & dry	57.7[a]	2.55[a]	34.26	9.44
(90 days)	54.6[b]	2.76[b]		
Wet & dry	52.3[a]	2.18[a]	20.58	6.64
(90 days)	39.3[b]	2.72[b]		

[a] Average result.
[b] Individual result.

specimens exposed to the various aggressive environments. For 28 days after casting, all specimens were sprayed twice daily.

According to ESS, the specimens should be tested at age 28 days. It is worth mentioning that the method of testing in the ESS is the same as that in the ASTMC140. However, the ASTM states that only three specimens should be tested and did not mention the method of curing nor at what age should the specimens be tested [12].

The results indicate that average compressive strength was slightly influenced pertaining the blocks which were immersed in 1% HCl, while increased for the other three mixes when compared to the control mix (age 90 days) as chemical reaction is a function of time to acquire a more stiffening binding material as cement hydration continues. The immersion in 1% HCl caused compressive strength to be reduced by 3.4%. This can be considered a minor influence on compressive strength. The 5% HCl solution increased compressive strength by 11.6% when compared to the control mix at age 90 days. The increase in compressive strength may be attributed to the possibility that 5% HCl solution may have acted as an accelerator, which accelerates early strength development. The air and dry as well as the wet and dry conditions also gave higher compressive strength when compared to the control mix by 16.9% and 6.7%, respectively. The increase in compressive strength during the air and dry condition may possibly be explained by the fact that drying in oven may have increased its rate of strength development of, since an increase in the curing temperature accelerates the gain of strength. The same explanation may be applied regarding the wet and dry condition. The results of the wet and dry conditions agrees with findings of Yang et al. [11].

Yang et al. investigated the effects of two different cyclic wetting and drying regimes as well as the effects of temperature during wetting and drying cycles on self-healing engineered cementitious composites. The results showed that the effects of temperature during wetting and drying cycles led to an increase in the ultimate strength but a slight decrease in the tensile strain of rehealed pre-damaged specimens.

According to the ESS, there are three categories for paving units based on compressive strength, and water absorption percentage. The three categories are; heavy duty, medium duty, and normal duty. The limits of the various physical properties are shown in Table 9.

The ASTM C 936 [13] criteria is the same as the ESS criteria for heavy duty. In other words, the ASTM does not have the medium and normal duty categories.

The control sample falls in the category of medium duty for both average compressive strength and individual compressive strength. The same apply for the samples that were immersed in 1% HCl as well as those who were exposed to the wet & dry condition. The specimens which were exposed to 5% HCl satisfied the first criterion of heavy duty but did not meet the second criterion. Therefore, it can be categorized as a medium duty. Both criteria of heavy duty were satisfied by the specimens which were exposed to the air and dry condition. The results are shown in Table 10 and Fig. 3.

Water absorption percentage

According to ESS, average water absorption for normal duty paving units should not be greater than 8% with no individual block greater than 10%. ASTM states that the average absorption of test samples shall not be greater than 5% with no individual unit greater than 7% [12]. It should be noted that ASTM does not categorize paving units as does the ESS.

The ESS and ASTM standards require that the specimens be immersed in water at temperature 15.6–26.7 °C for 24 h after which the specimens are weighed to obtain the saturated weight. Subsequent to saturation, the specimens are dried in a ventilated oven at 100–115 °C for 24 h. The specimens are then weighed to obtain the oven-dry weight.

The test results show that the four aggressive environments reduced average absorption percentage when compared to the control mix at both ages. However, the comparison regarding water absorption will be applied on specimens of age 90 days The reduction in average water absorption was 67.2%, 61.3%, 36.3%, and 45.5% for 1% HCl, 5% HCl, air & dry, and wet and dry conditions, respectively.

As expected, average water absorption was reduced for the different aggressive media, possibly due to the fact that the control mix was stored at room temperature after 28 days of casting, while most probably hydration continued for specimens at a higher rate due to the presence of solutions. The traditional trend between product absorption percentage and product compressive strength was fulfilled to a certain extend as both properties are inversely proportional.

The control sample can be classified as medium duty due to the fact that the average absorption percentage was slightly higher than that required by the ESS (7% higher). The four environmental aggressive conditions resulted in water absorption percentages that met the criteria of heavy duty. See Table 10 and Fig. 4.

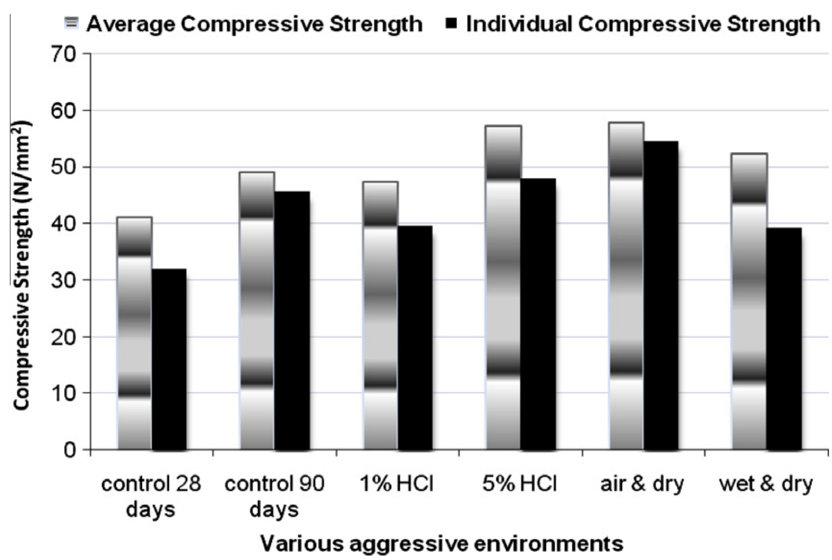


Fig. 3 Effects of aggressive environments on compressive strength.

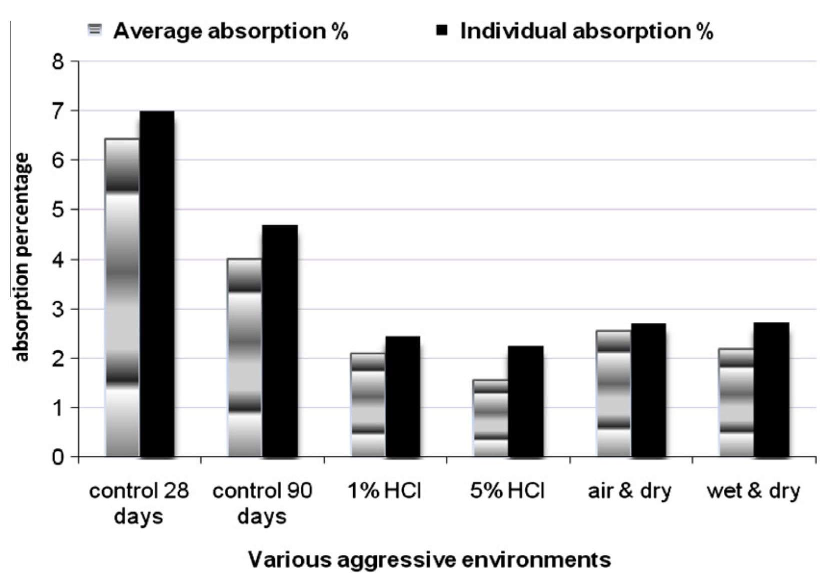


Fig. 4 Effects of aggressive environments on absorption percentage.

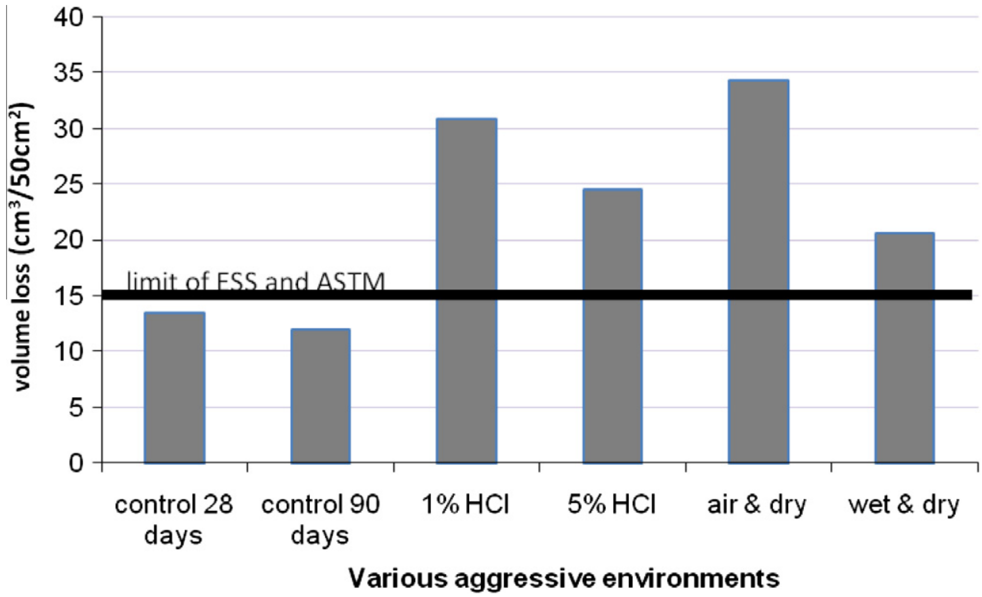


Fig. 5 Effects of aggressive environments on volume loss.

Abrasion

Abrasion of paved areas is directly proportional to pedestrian volume rather than vehicular traffic. Higher abrasive wear is likely in highly-concentrated pedestrian areas such as corridors, entries/exits, automatic teller machine and the like.

Australia and New Zealand classify pavers by their exposure grade. AS/NZS 4456.10 (Determining Resistance to Salt Attack), Standard is used to determine the exposure grade.

During the test, the samples are immersed in a salt solution for a number of cycles and the performance of the paver is observed. The suitability of the units for use in a given environment determines their durability grade or salt attack resistance category [14].

Temperature variations results in changes in concrete volume. In case, concrete is unrestrained, normal volume changes would have insignificant consequences.

Daily changes in temperature can be up to 20 °C at the coast and somewhat higher inland.

Seasonal changes in temperature are usually greater than the daily fluctuations. Seasonal temperature changes may range up to 50 °C between the summer and winter. Seasonal temperature changes causes higher stresses than daily temperature changes, and eventually may result in cracks. Also, the moisture content in concrete may result in either expansion or contraction. As concrete dry the portion of concrete near the surface dry and contract faster than the inner portion possibly causing the surface to develop tensile stresses and possible cracks [15].

The abrasion resistance test was carried out by sandblasting. This procedure simulates the action of waterborne abrasives and abrasives under traffic on concrete surfaces. It is worth mentioning that the test procedure dictated by the ESS [16] is the same as that of the ASTM C418 [17]. Also the limits of the Egyptian Standard is the same as that of the ASTM C936 which covers the requirements for interlocking concrete paves manufactured for the construction of paved surfaces. In other words, ASTM C418 covers the testing procedure while ASTM C936 states the limits. The ESS, on the other hand, comprises two parts: part one covers the requirements for the three parameters: compressive strength, water absorption, and abrasion resistance; while part two covers the testing procedure for the three parameters.

The limits are shown in Table 9. It should be noted that the limits apply to the three categories of paving units in the ESS and ASTM. Figs. 5 and 6 illustrate the effects of aggressive environments on volume loss and thickness loss respectively. Table 10 shows the test results.

The volume loss criterion was satisfied by the control specimens at age 90 days while the second criterion, which is the loss in thickness, was 10% greater than required by the ESS and ASTM standards. The specimens which were exposed to the four aggressive environmental conditions did not satisfy both criteria of ESS and ASTM.

The increase in volume loss was 157%, 104%, 185.5% and 71.5% for 1% HCl, 5% HCl, air & dry as well as wet & dry conditions respectively when compared to the control mix at age 90 days. The average thickness loss also increased by 150%, 119%, 195%, and 107.5% for 1% HCl, 5% HCl, air & dry and wet & dry conditions respectively when compared to the control mix at age 90 days. The increase in both criteria may possibly be attributed to the formation of $Ca_2{\cdot}Al(OH)_6Cl{\cdot}2H_2O$ in case of acid HCl solution which causes softening in the surface of the samples. In other words, the chemical attack was limited to a superficial zone as indicated by X-ray diffraction. In the case of air & dry and wet and dry conditions, the increase in both criteria may possibly be explained by the loss of moisture which retard cement hydration as well as result in the development of tensile stresses on the surface and ultimately weakening the surface. It worth mentioning that both criteria concerning abrasion have the same limits regardless of product compressive strength and absorption percentage.

Physico chemical reactions

Chemical reaction plays an important role in chemical durability tests. The benefit of the addition of cement to lime

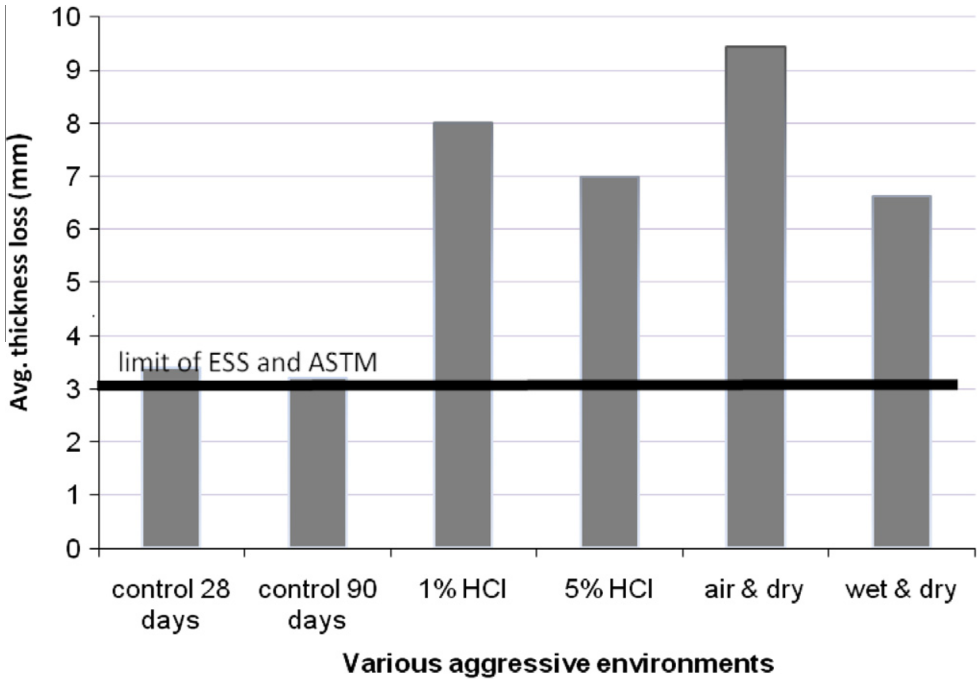
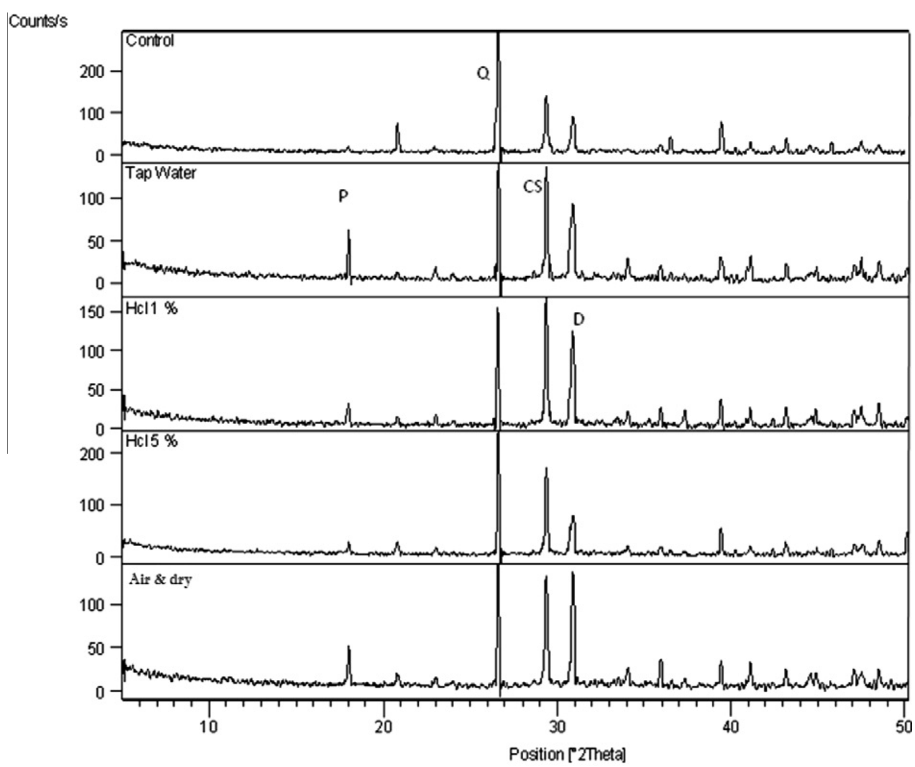


Fig. 6 Effects of aggressive environments on thickness loss.



P: Portlandit
Q: Quartz
CS: Tricalcium silicate
D: Dolomite

Fig. 7 XRD X-ray diffraction for the various aggressive environments. P: Portlandit, Q: Quartz, CS: Tricalcium silicate, D: Dolomite.

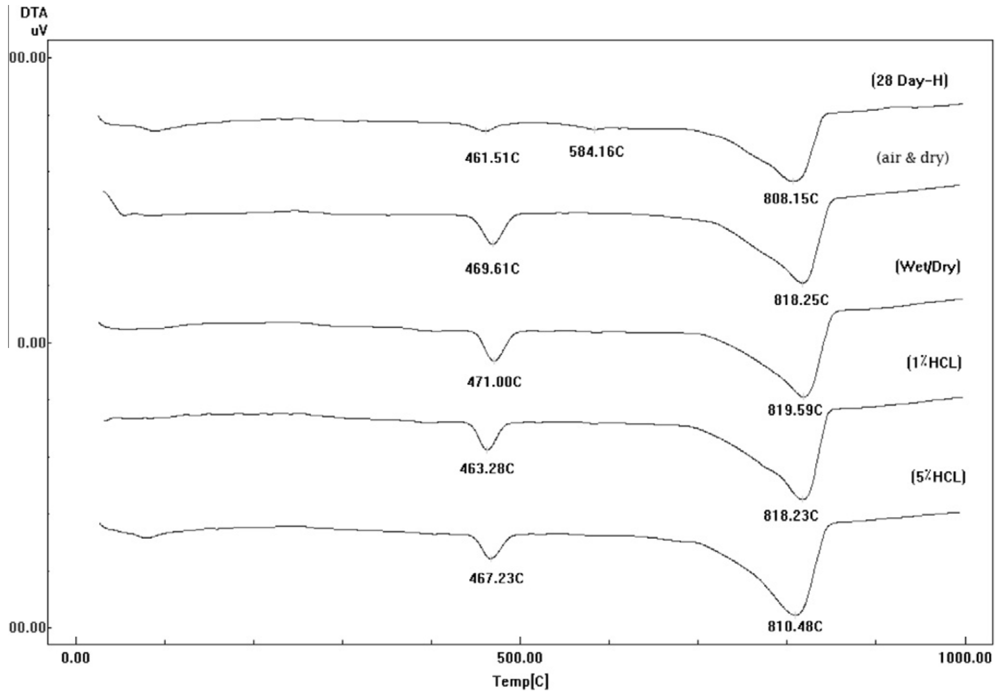


Fig. 8 DTA-thermographs for the various aggressive environments.

aggregate (crushed lime stone, marble powders, and fine aggregate is to improve the properties and performance of sand. Four mechanisms can be observed in the mix that contains cement, lime, and sand. These include (1) cation exchange, (2) locculation/agglomeration/solidification, (3) carbonation reaction and (4) pozzolanic reaction.

X-ray diffraction technique was used to identify the mineralogical composition of the specimens as presented in Fig. 7. The mineralogical structure of the interface zone can be improved further with time by the secondary reaction the $(Ca(OH)_2$ present forming C–S H, thus leading to even denser interface zone with better durability. The mineralogical composition shows that both ratios of HCl did not combine with the original constituent materials in the backing layer (main layer) as no salts were indicated in the figure. Thus, this result supports what has been previously mentioned concerning the chemical attack to perhaps have taken place on the surface only, since compressive strength was high regarding the concerned specimens despite the fact that abrasion criteria was negatively affected.

Phase composition of the formed hydrates

The DTA of the investigated paving blocks indicates that at peak temperature of 584.16 °C, $(\alpha - \beta)$ quatrz appeared for the control sample, while disappeared for the other four mixes. At peak temperature of 461 °C, calcium hydroxide appeared for the control sample. Calcium hydroxide also appeared for the other four mixes at peak temperature ranging from 463 to 471. These results are in good agreement with the results of compressive strength as the formation of calcium hydroxide indicates that the process of hydration is continuing.

The DTA-thermographs are shown in Fig. 8. The phases denote the presence of calcium hydroxide which forms calcium silicate hydrate (C–S–H) which, in turn, responsible for the production of a more dense paving units, and is also responsible for the formation of calcium chloride, on the surface of the sample when soaked in (1% and 5%) HCl $\cdot CaCO_3$ decomposes at temperature 808.15 °C and its decomposition increases with the various soaking media. However, the decomposition was more pronounced in (1% and 5%) HCl.

Conclusions

Based on the experimental results obtained from this study, the following conclusions can be drawn.

(1) The immersion in 1% HCl and 5% HCl solutions increased compressive strength by 3.4% and 11.6%, respectively when compared to the control mix.
(2) Air and dry as well as the wet and dry conditions also gave higher compressive strength when compared to the control mix by 16.9% and 6.7% at age 90 days, respectively.
(3) The specimens which were exposed to air & dry condition are the only ones that satisfied the criteria for heavy duty concerning compressive strength.
(4) The control mix as well as the mixes exposed to 1% HCl, 5% HCl solutions, and wet and dry condition satisfied the criteria for medium duty pertaining compressive strength.
(5) The four aggressive environments reduced average absorption percentage when compared to the control mix.

(6) The control sample can be classified as medium duty (at age 28 days) according to Egyptian Standard Specifications for water absorption limits.
(7) The four environmental aggressive conditions resulted in water absorption percentages that met the criteria of heavy duty.
(8) Concerning abrasion, the volume loss criterion was satisfied by the control specimens while the second criterion, which is the loss in thickness, was slightly greater than required by the ESS and ASTM standards.
(9) Samples which were exposed to the four aggressive environments conditions did not satisfy both criteria of ESS and ASTM pertaining abrasion.
(10) X-ray diffraction test indicated that the chemical attack was likely to be superficial as compressive strength was high, while, on the other hand, abrasion criteria were negatively affected pertaining the four aggressive media.

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