

# Effect of Iron Slag on the Corrosion Resistance of Soda Lime Silicate Glass

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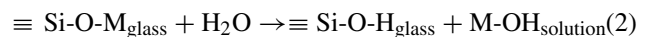
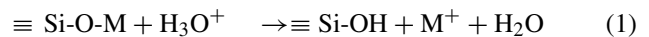
**Abstract** Soda lime silicate glasses containing different amounts of iron slag 0–30 % were prepared. The chemical durability of the prepared glasses was examined by immersion in HCl or HNO<sub>3</sub> solutions at room temperature. The results show that the glass durability increases with increasing the amount of slag in the glass composition to a certain amount, then followed by a decrease in the glass durability. Various mechanisms of corrosion and the role of the mobility of cations and their leaching into solution, also the effect of time of leaching are discussed. The densities of all glass compositions were measured. The quantitative analysis obtained from infrared absorption spectra in the range of (400–4000) cm<sup>-1</sup> in relation to the effect of corrosion on the absorption spectra has been studied in terms of structural concepts. The topography of the glass surfaces was observed by scanning electron microscopy (SEM). The concentration percentage of the ions present on the glass surface was determined by Energy Dispersive X-ray analysis (EDX).

**Keywords** Silicate glass · Iron slag · Glass durability · SEM

## 1 Introduction

High durability is desired because even minor surface dissolution can lead to surface roughness and degradation of the optical quality of glass [1]. However, improving the durability of glass by changing its composition can lead to a prohibitively high working temperature and therefore, when formulating a commercial glass composition a compromise is made between durability and workability.

The durability of glass in an aqueous environment is a function of the kinetic approach to equilibrium and the final thermodynamic equilibrium with the aqueous environment [2], the kinetics of the glass dissolution depend on the test parameters (surface area, time, temperature) while the thermodynamic contribution is a function of glass composition and structure [3], also it depends on the pH of the solution used. The mechanisms of dissolution of glass are generally described in two stages. The first stage is an ion exchange at the glass surface of an alkali M (or possibly alkaline earth) ion in the glass with a hydrogen ion or hydronium ion (H<sub>3</sub>O)<sup>+</sup> in the attacking solution according to the following reactions:



The surface of the glass becomes depleted in alkali, and a silica-rich layer is formed. The changes in the solution depend on whether or not the aqueous system is closed or open, and the surface area of the glass exposed to the solution [4]. In a closed system, the solution pH increases. Also the rate of dissolution increases with increasing pH, so dissolution accelerates with time in such a closed system, which is the present case.

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**Table 1** Chemical composition of the studied glass (wt.%) doped with different amounts of slag

Glass no.	SiO <sub>2</sub> %	Na <sub>2</sub> O %	CaO %	Slag (added to 100 % glass)
G1	70	20	10	–
G2	70	20	10	5
G3	70	20	10	10
G4	70	20	10	15
G5	70	20	10	20
G6	70	20	10	30

Blast furnace slag is one of several wastes that affect the environment; where the annual world production of slag is almost 150 million metric tons [5]. In this study we are trying to get rid of an environmentally harmful industrial waste by making a durable glass. Ideally, we want to describe how changing the amount of each chemical component changes the glass structure and how these structural changes affect durability as well as other diffusion processes. However, because it is impossible to directly observe changes in glass structure, observations are made on changes in properties that are then used to understand possible changes in structure.

The work includes the estimation of the chemical durability of silicate glasses containing up to 30 % addition of iron slag. The study is confirmed by IR spectral measurements and SEM studies.

## 2 Experimental

The composition of the studied glasses is shown in Table 1, glasses from G2 to G6 contain slag as an addition to the base glass. All glasses under investigation were prepared from pure chemical reagents except Blast Furnace Slag (BFS), (Table 2) produced by Egyptian Iron and Steel Co., Helwan, which was introduced as a waste product. SiO<sub>2</sub> was added as pure silica, calcium and sodium oxides were added in the form of their corresponding carbonates. The melts were all made in platinum 2 % rhodium crucibles in an electrically heated furnace in atmospheric air at temperatures ranging from 1200 to 1350 °C ± 20 °C depending on glass composition for four hours. After complete melting, the glass was cast in a stainless steel mold of dimensions 1 × 1 × 0.5 cm<sup>3</sup>.

**Table 2** Composition of iron slag from Egyptian Iron and Steel Co. in wt.%

Oxides	SiO <sub>2</sub>	CaO	Na <sub>2</sub> O	Al <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	Fe <sub>2</sub> O <sub>3</sub>	BaO	MnO	SO <sub>2</sub>
	34.05	35.5	4.34	13.49	1.53	1.98	0.51	1.4	5.5	1.7

The molten glass was annealed at the appropriate temperature of about 400 °C, according to the literature [3]; the furnace was left to cool at a rate of 30 °C/hr ± 5 °C down to room temperature.

To study the corrosion behavior of the glass under extreme conditions, solutions of 1.0N or 3.0N HCl or 1.0N HNO<sub>3</sub> were used as leaching media. The experiment was performed at room temperature for different times up to 312 hours.

For each experiment a glass sample, having the same size and consequently almost the same weight, was placed in a polyethylene beaker containing 40 cm<sup>3</sup> of leaching solution. The glass samples were washed with distilled water and dried in a vacuum oven at 80 °C for 30 minutes then left to cool. The samples were carefully weighed before and after being immersed in the used solution (1.0N or 3.0N HCl or 1.0N HNO<sub>3</sub>) and the weight loss was calculated.

The infrared absorption spectra were measured in the range 4000–400 cm<sup>-1</sup>, using the KBr technique with a Maten 100 spectrophotometer (Unicom Co. Ltd., England), the glass samples were measured before and after immersing in different concentrations of leaching solutions (1 and 3N) of HCl, and 1N HNO<sub>3</sub>.

The density of the glasses was determined by the Archimedes method using xylene at 20 °C.

A scanning electron microscope (JEOLSM – 54000) was used to study the surface morphology of the specimen at high magnifications. The glass samples were plated by a very thin gold layer before examination. EDX was used to identify the elements in the specimen surface and their percentage.

## 3 Results and Discussion

### 3.1 Effect of Glass Composition on the Glass Durability

The addition of slag to the base soda lime glass causes a change in the glass composition as shown in Table 3. The results in Figs. 1, 2, and 3 show that the addition of small amounts of slag causes an increase in the glass durability. The difference in behavior between the durable and non-durable glasses can be related to the levels of the glass former and the glass modifier within the glass composition. In other words the addition of any network former will generally tend to improve the chemical durability and increase the field strength or polarizing power of the glass. Certain

**Table 3** Real calculated glass composition in wt.%

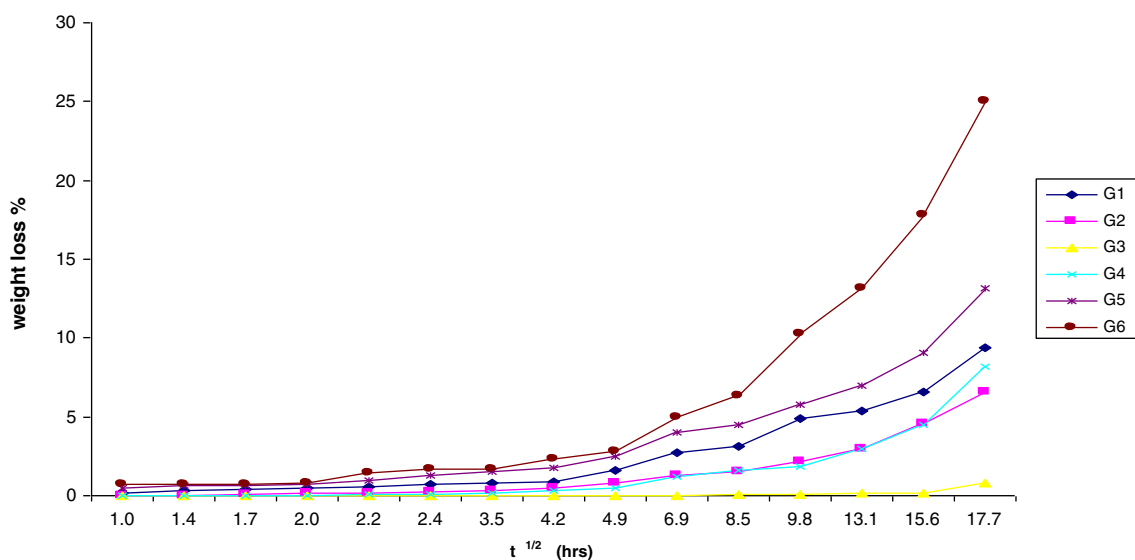
Oxides Glass no.	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	Al <sub>2</sub> O <sub>3</sub>	MgO	MnO	BaO	Fe <sub>2</sub> O <sub>3</sub>	SO <sub>2</sub>
G1	70	20	10						
G2	68.2	19.1	11.2	0.6424	0.167	0.058	0.212	0.063	0.08
G3	66.7	18.2	12.3	1.226	0.033	0.117	0.433	0.13	0.153
G4	65.3	17.5	13.3	1.8	0.5	0.175	0.635	0.19	0.231
G5	64.0	16.8	14.3	2.2	0.6	0.23	0.85	0.25	0.31
G6	61.7	15.5	15.9	3.1	1.0	0.4	1.27	0.38	0.46

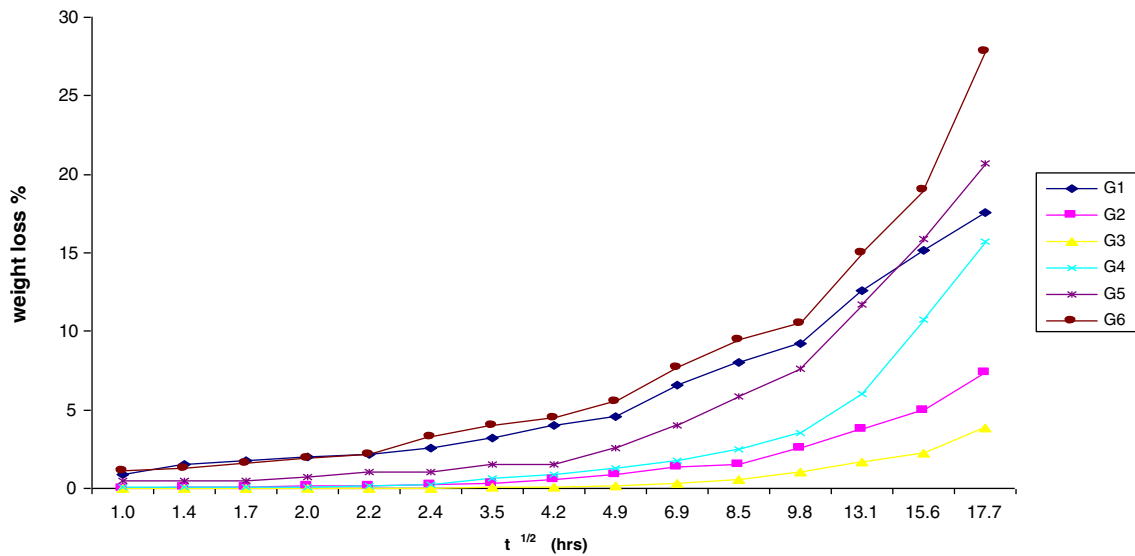
added cations can cause the same effect [6]. This is what is happening when the slag is added to the soda lime glass as shown in Figs. 1–3 where the sodium content (the most soluble ion) decreased by replacing it by aluminum which may act as a glass-former and less soluble ion.

According to Greaves [7], the modifying alkali cations have well defined local structure in the modified random network model. Modifying cations or metal ions occupy percolation channels weaving between the network parts of the structure. These channels are the most likely routes for cation-diffusion, ion exchange and infusion of water. The presence of divalent cations with relatively large ionic radii is assumed to inhibit the diffusion and progress of the corrosion mechanisms to some extent. According to Lehman [8], the relative effect of the different divalent oxides is expected to depend on the ionic radius of the respective divalent cation. This together with the possibility that some cations may have the ability to form an insoluble thin layer prohibiting further attack and increasing the durability of the glass, e.g. when calcium oxide replaces sodium or lead

oxide in soda lime lead-silicate glass. It was observed by Lehman that there is retardation in the release of lead from lead-silicate glasses. It was postulated that the chemical durability of glass is often interpreted in terms of the glass network structure [8].

A highly cross-linked structure is usually more durable than one composed of linear chains or simply clusters of molecules [9]. For further increase of the slag content (more than 10 %) in the glass composition note that there is a decrease in its durability. This may be due to inhomogeneous arrangement in the glass structure as a result of introducing large ions such as aluminum, calcium, magnesium, barium or iron instead of a small ion like sodium ion. These large ions can block the routes for the diffusion of the attacking leaching ions, when they are added in small amounts, while increasing these constituents causes the expected inhomogeneous arrangements producing a more open structure that can be easily attacked by the corroding ions. Haha et al. [10] found that adding Al<sub>2</sub>O<sub>3</sub> content in slag up to 2 % causes an increase in the compressive

**Fig. 1** Effect of 1N HCl on different compositions of glass for different time intervals at room temperature

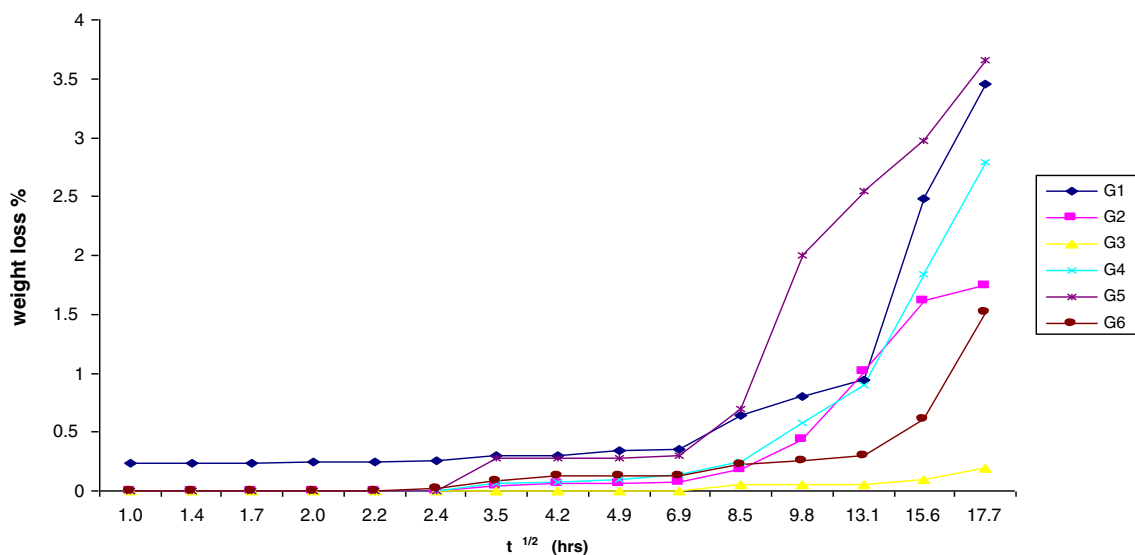


**Fig. 2** Effect of immersing glass in 3N HCl for different time intervals at room temperature on the weight loss of different glass compositions

strength, while the addition of 15 %  $\text{Al}_2\text{O}_3$  did not cause any further increase in the compressive strength. This result shows that although aluminum ions have high compressive strength, there is a limitation to improving this property by adding more than 2 % aluminum oxide, which supports the assumption of inhomogeneous arrangements with increasing aluminum content.

Also according to Table 3 note that many Si and Na ions have been replaced by larger ions such as Ca, Al, Mn and Ba. This will also lead to a greater number of non bridging oxygen that decrease the connectivity of the structure combined with the relatively high mobility of the alkali ions [4]. It is expected that under the experimental conditions the proposed inhomogeneity may increase the effective surface

area of the glass. This can cause an increase in the rate of dissolution of the glass, in conjunction with the presence of sodium ions. Leaching of silicate glass in acidic solutions includes preferential extraction of alkali ions from the glass surface into solution. This leaching entails the substitution of hydrogen-bearing ions [protons ( $\text{H}^+$ ) or hydronium ions ( $\text{H}_3\text{O}^+$ )] for alkali ions in the glass surface leaving behind a silica-rich layer containing hydrated micropores. This silica-rich layer may be partially or completely depleted of alkali and/or alkaline earth ions. In relatively durable glasses, such as soda-lime-silicate glasses, this substitution in which the remaining constituents are not altered occurs without changing the network structure of the surface hydrated layer of the glass.



**Fig. 3** Effect of immersion glass in 1N  $\text{HNO}_3$  for different time intervals at room temperature on the weight loss of different glass compositions

**Table 4** Density (gm/cm<sup>3</sup>) of the studied glasses

Glass no.	G1	G2	G3	G4	G5	G6
Density	2.695	2.701	2.751	2.765	2.771	3.102

The last assumed inhomogeneity can be confirmed by comparing the composition of G3 and G5 in Table 3 to the untreated samples in Table 5, where the amount of each of Fe<sub>2</sub>O<sub>3</sub>, MnO and BaO (which are the largest ions in the glass composition) are greater in Table 3 which represents the wt% of the addition of these elements to the glass composition. Note that in Table 5 both Fe<sub>2</sub>O<sub>3</sub> and MnO are not detected while the amount of BaO is 0.08 % in the glass surface of G5, which means that these ions diffused through the glass network structure. Doremus [11] proposed another model in which the rate of leaching of less durable glasses is controlled by the rate of diffusion of water molecules into the hydrated layer.

Ernsberger [12] proposed a corrosion mechanism that incorporates both ion-exchange and molecular water. Accordingly, three species', M<sup>+</sup> (e.g. Na<sup>+</sup>), molecular water and hydronium ions are involved as represented by Eqs. 1, and 2. The attack of water resembles the attack by acids. However, they differ in two respects. Firstly alkali liberated from the glass is progressively neutralized. Secondly, the modifying oxides such as CaO, MgO and BaO are more soluble in acid solutions and therefore more readily leached in acidic solutions.

The stages of the corrosion mechanism can be suggested to proceed as follows:

1. Ionic bonds between the alkali cations (and to some extent alkaline earth cations) and anionic nonbridging oxygens [Si-O<sup>-</sup>] must be broken.

2. The alkali cation (or a divalent cation) must have unobstructed pathways to migrate between different sites in the glass structure. Hydration of glass during leaching results in the protonation of Si-O<sup>-</sup> to form a silanol Si-OH group.

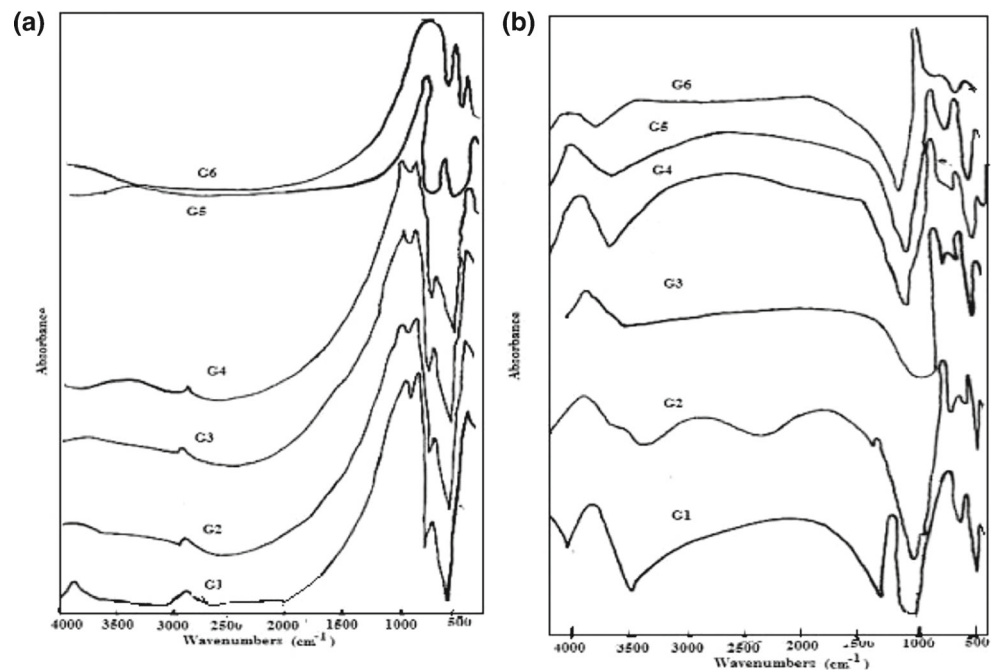
When Si-OH is produced, a M<sup>+</sup> (alkali cation) is free to migrate when it passes a Si-OH group, but it can be trapped when it passes a Si-O<sup>-</sup> site and consequently inhibits the diffusion process. Therefore, one parameter controlling the diffusion is the ratio of Si-O<sup>-</sup> to Si-OH established in the hydrated glass surface. It has been established that [13] the first step in dissolution of a silicate glass is the partial hydration reaction of water with the silicon-oxygen network. After hydration, some glasses form a more open surface layer, allowing greater access of water molecules to the silicon-oxygen bonds. It was also proposed by Perera et al. [14] that the hydration reaction occurs at activated sites on the glass surface and it may continue until parts of the glass are detached from the network. It was also assumed by the same authors that there is evidence that colloidal islands larger than molecules dissolve first and finally hydrolyze to silicic acid.

The relative effects of different acids on the chemical durability of the glass represented in Figs. 1–3 can be correlated with differences in the degree of dissociation of the acids or to the tendency of solubility of the formed components in acids. It is also found [11] that the extraction rate of the different constituents from glass not only depends on the type of acid but also on the acid concentration as well. The pronounced increase in the glass durability in nitric acid over hydrochloric acid can be ascribed to the higher ionization constant of hydrochloric acid than that of nitric acid (where the acidity constant of HCl = 10<sup>7</sup>, while HNO<sub>3</sub> = 200 [15]).

**Table 5** Chemical composition in wt.% of the surface of G1, G3 and G5 before and after immersion in different(HCl) concentrations for 312 hours by means of EDX

Glass number	G1			G3			G5		
	Untreated	1N HCl	3N HCl	Untreated	1N HCl	3N HCl	Untreated	1N HCl	3N HCl
SiO <sub>2</sub>	42.22	73.17	71.98	48.00	78.60	90.60	48.26	76.85	74.75
CaO	30.91	14.40	10.85	15.20	1.97	0.64	5.65	4.88	5.96
Na <sub>2</sub> O	26.87	12.43	17.17	32.08	12.19	1.92	37.85	10.2	14.56
Al <sub>2</sub> O <sub>3</sub>				1.90	0.00	0.0	2.97	0.74	0.0
MgO				1.60	0.75	0.0	4.40	0.70	1.02
K <sub>2</sub> O				0.16	0.0	0.0	0.36	0.0	0.16
Fe <sub>2</sub> O <sub>3</sub>				0.33	0.0	0.0	0.0	0.39	0.0
BaO				0.25	2.32	2.91	0.08	2.98	1.31
MnO				0.40	0.0	0.0	0.0	0.0	0.0
SO <sub>2</sub>				0.11	4.16	3.94	0.79	3.26	2.2

**Fig. 4** Infrared absorption spectra of all investigated glasses. **a** Before being immersed in 1N HCl. **b** After being immersed in 1N HCl for 312 hours



### 3.2 Density

The specific volume of glass was among the first properties to be calculated on the basis of chemical composition [16]. Since silicon and sodium oxides form the main bulk of the glass studied, the density of these glasses is essentially determined by the properties of these two oxides. In the alkali silicate glasses, the introduction of soda to silica results in the formation of single-bonded or non-bridging oxygen atoms, i.e., oxygen linked to only one silicon atom. The sodium ions are linked to the surrounding oxygens by bonds which are much more ionic and also much weaker than the silicon-oxygen bonds. It can be noticed from the results (Table 4) that the glass density increases as the slag is introduced to the glass structure. This can be explained on the basis of the slag composition, which mainly consists of silicon, calcium, aluminum and barium oxides. As the concentration of aluminum oxide increases the opportunity arises for  $\text{Al}^{3+}$  ions to assume fourfold coordination as  $\text{AlO}_4$  groups, which strengthen and give compaction to the glass network. Barium ions are normally housed in the glass interstices and these large and divalent  $\text{Ba}^{2+}$  cations become more strongly held in the interstices than the  $\text{Na}^+$  ions. The groups of  $\text{SiO}_4$  tetrahedra around the divalent cations become more stable than the same groups which might be found around the monovalent cations. Consequently, the structure is expected to develop a series of interstices of more or less regular type surrounding the  $\text{Ca}^{2+}$  and  $\text{Ba}^{2+}$  cations with a proportion of large irregular interstices in which  $\text{Na}^+$  ions are housed, possibly with more than one  $\text{Na}^+$  ion in each of the large, irregular rings.

As a result, sodium ions are comparatively weakly held in the structure, and most of the more regular interstices are occupied by divalent cations.

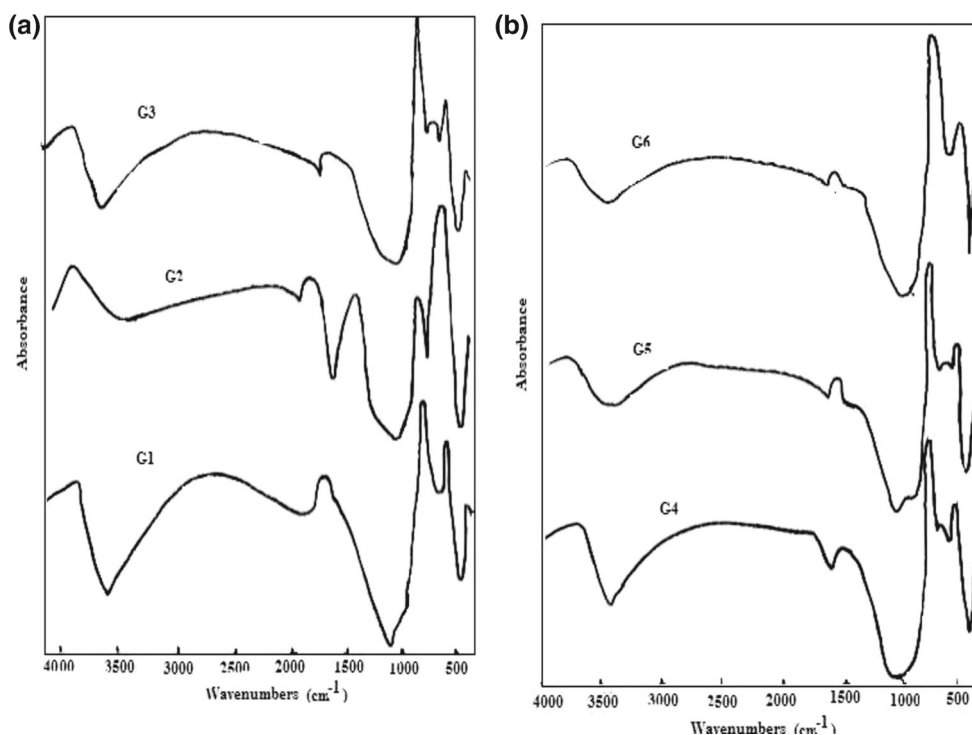
However, when the slag content is increased, there will be inhomogeneity in the structure arrangement, which may cause a volume increase and consequently a decrease in the glass density. But according to the results given in Table 4 it is evident that the density increases; this can be attributed to the increase of ions with higher atomic weights such as manganese and barium existing in the slag replacing silicon and sodium ions in the base glass. This increase in the atomic weight is greater than the volume increase caused by the inhomogeneous arrangement of the glass structure, which is the reason for the observed increase in the glass density since the density of glasses is controlled by the free volume and the masses of the ions present [9].

### 3.3 Infrared Absorption Studies

#### 3.3.1 Effect of Composition

The infrared spectra of silicate glasses consist of at least three bands localized around 1033, 800 and 470  $\text{cm}^{-1}$ , that are characteristic of the silica network. For the vibration of isolated  $\text{SiO}_4$  tetrahedra, bands at 1033 and 470  $\text{cm}^{-1}$  correspond to stretching and bending modes. The absorption bands at 450–500, 750, 850–900, 1000–1050, 2850–2950 and 3500–3970  $\text{cm}^{-1}$  may be attributed to Si-O-Si bending vibrations, bond bending vibrations of bridging oxygen atoms, stretching vibrations of Si-O bonds within the tetrahedral groups containing non bridging oxygen,

**Fig. 5** Infrared absorption spectra of glasses after immersed in 1 N HNO<sub>3</sub> for 312 hours **a** G1&G2&G3 **b** G4&G5&G6



Si-O-Si vibrations, stretching vibration of disilicate vibrations, SiO<sub>6</sub> octahedral group vibrations, strongly hydrogen-bonded OH stretching vibrations and fundamental free OH stretching vibrations, respectively [17]. The change in the position and intensity of all the previous absorption bands may be due to different modes of vibrations, of silicate groups.

From the results illustrated in Fig. 4 note that only for glasses G3 and G4 does the band at about 3500 cm<sup>-1</sup> disappears. This represents the physically absorbed water and OH groups.

The addition of slag in the glass apparently introduced Al<sub>2</sub>O<sub>3</sub>, CaO, MgO, BaO and traces of other oxides besides SiO<sub>2</sub>. Thus any shift of this high frequency envelope (1000 – 1050, 2850 – 2950 cm<sup>-1</sup>) can be correlated with either a gradual shift in the Si-O stretching frequency or a superposition of discrete bands due to Si(OAl)<sub>x</sub> units, where x is the number of aluminate tetrahedra adjacent to a silicate tetrahedron.

Note that there is no major change in the spectra due to the addition of slag to the base glass. These results indicate that the substitution of sodium oxide by CaO, BaO or MgO gives no change in the main structural building groups and the skeleton of the glass network remains the same. However, such cations often have weak IR modes which are superimposed on the one strong IR band of the glass network [18, 19]. MgO is believed to be able to share partly in forming structural building MgO<sub>4</sub> groups. Such groups

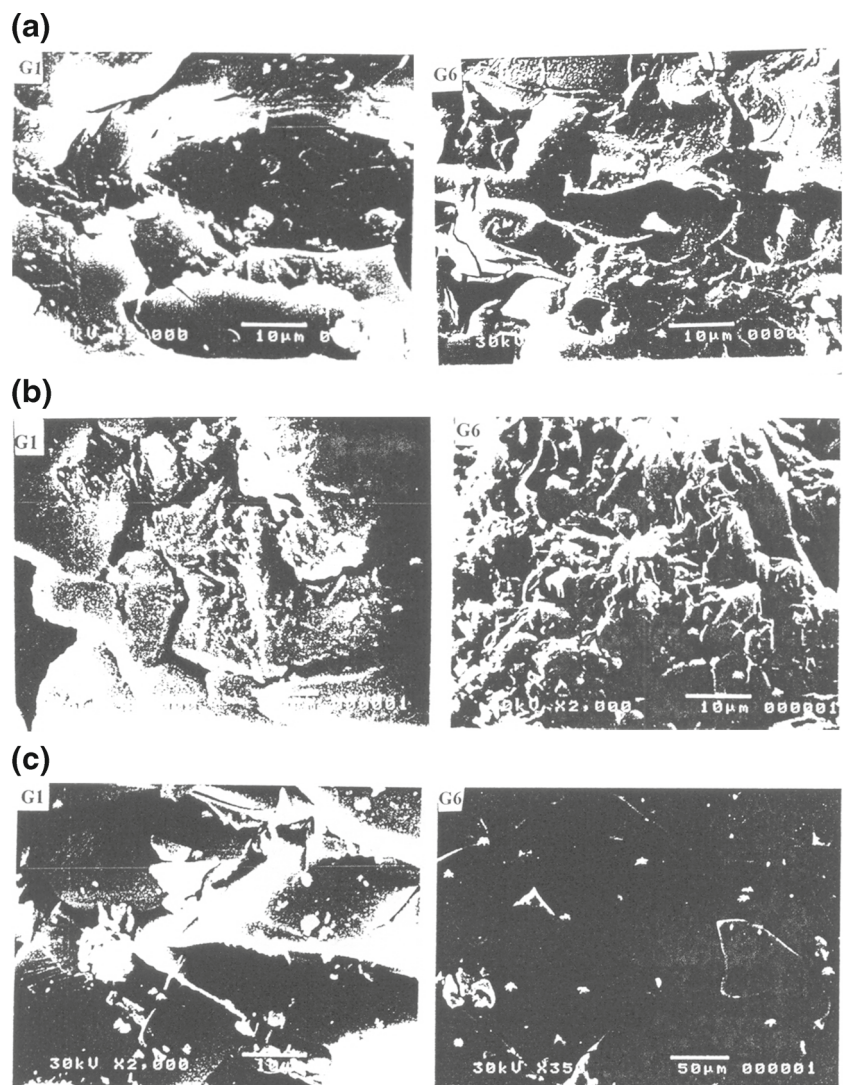
are assumed to vibrate in the low frequency region (below 400 cm<sup>-1</sup>) and outside the present measurements [20].

Also the other oxides namely CaO and BaO are known to be situated in interstitial positions as network modifiers. The vibration frequency of a molecular unit is directly related to the force constant associated with the cation–anion bonds. The force constants for M-O bonds (M = network modifier) are lower than those for T-O bonds (T = network former) because modifiers have lower charge and reside in large, high–coordination sites. The modifying cation vibrations would therefore be expected to be at lower frequency than the vibrations of the tetrahedral framework [17]. It is therefore accepted that the vibrations of the BaO and CaO are active and located in the low frequency region. The net result of the variations of the chemical compositions of the soda lime glasses by replacing some of its Na<sub>2</sub>O-by BaO or MgO reveals only minor shifts of the absorption bands, but the major characteristic absorption bands remain persistent. Further increase of the slag content in the glass composition results in an increase of the CaO and Al<sub>2</sub>O<sub>3</sub> content.

### 3.3.2 Effect of Leaching

Infrared spectra of the untreated and leached glass samples are shown in Figs. 4 and 5. The band at around 3500 cm<sup>-1</sup> may be attributed to physically absorbed water in the glass surface. In the corroded glass, the observed intense O-H band may either be due to the higher amount of water

**Fig. 6** SEM micrograph for glasses (G1 and G6) **a** after being immersed in 1 N HCl for 312 hours **b** after being immersed in 3 N HCl for 312 hours **c** after being immersed in 3 N HNO<sub>3</sub> for 312 hours



absorbed on the glass surface or the Si-OH bond formed between the absorbed water and Si-O on the glass surface. However, because of the overlap between the H<sub>2</sub>O and OH bands at 3500 cm<sup>-1</sup>, one cannot be sure about the nature of the OH in this region. The bands observed around 2800–2930 cm<sup>-1</sup> may also be attributed to the Si-OH bonds formed between the absorbed water molecules and the Si-O molecules on the glass surface.

A new band is formed at 1500–1750 cm<sup>-1</sup> for glass leached in HNO<sub>3</sub>. This band may be attributed to molecular water as reported by Sander et al. [21]. Note also that the band at 2850–2950 cm<sup>-1</sup> disappeared; leading us to expect that the mechanism of glass corrosion may include some sort of water diffusion in the case of leaching in HNO<sub>3</sub>. Alternatively the leaching by HCl solution may result from a mechanism which only involves ion exchange between H<sup>+</sup> and M<sup>+</sup> or M<sup>2+</sup> respectively.

The band at 450 cm<sup>-1</sup>, representing the Si-Si bending which shows almost no change, as well as the band at

750 cm<sup>-1</sup>, which represents the Si-O-Si stretching vibration band, show almost no change either in intensity or wavenumber. This observation supports the assumption that the observed leaching is selective based on ion exchange involving the modifier content in the glass structure. Elmer [22] proved by analyzing the leaching of E-glass fibers that the amounts of non-silicate constituents removed increase with both time and acid strength. In order to maintain electrical neutrality, the ions that are associated with the original silica lattice are exchanged with H<sup>+</sup> ions from the solution. Their presence as OH groups in the hydrated glass is well recognized in the infrared absorption spectra.

### 3.4 Study of the Glass Surface

#### 3.4.1 Effect of Leaching Solution on Glass Durability

Figure 6 shows the optical micrographs of thin section of the glass surface, containing large voids and layers and



showing some whirling and ripple-like corrugations. Shot particles (i.e. teardrop-shaped and spheres) and large voids are found scattered throughout the material. Large voids are believed to have formed in regions where small ions bridged together with sufficient strength to resist the consolidation stresses. The plane was strongly cross linked in a complex way and had approximately random orientations in the glass surface [11]. The leaching process which involves hydrogen-bearing ions and alkali ions in the glass surface leaves behind a silica-rich layer containing hydrated micropores. This can be noticed in Fig. 6a and b which represent the attack of different concentrations of HCl solution on the glass surface, while Fig. 6c shows almost no effect of HNO<sub>3</sub> solution. Table 5 shows the effect of immersing the base glass in 1 and 3N HCl solutions and the results show a remarkable decrease of the sodium content in the glass surface after being immersed in the acid solution for 312 hours. This result confirms the assumption that the sodium ion is the most soluble ion of the glass constituents. Table 5 shows the composition of glass containing 10 % & 20 % of slag (G3 & G5) respectively, when immersed in the same solution for the same time. It can be noticed that there is a large decrease in the glass modifiers as mentioned before, except for barium oxide, which means that for barium chloride is less soluble than the chlorides of sodium, calcium and magnesium.

#### 4 Conclusion

It can be concluded that soda lime silicate glass of composition 70 % SiO<sub>2</sub>, 20 % Na<sub>2</sub>O, 10 % CaO and containing 10 % slag (wt. %) has the best durability either in HCl or HNO<sub>3</sub>. It is notable that when the slag addition increased to 20 % or 30 % it causes deterioration in the glass durability. The results are interpreted assuming that the main factor affecting corrosion is the release of Na<sup>+</sup> ions in an ion exchange reaction, while increasing Ca<sup>2+</sup> ions causes a block in the percolation channels for the liberation of Na<sup>+</sup> ions resulting in a decrease in the amount of corrosion. When the slag addition amount increases to 20 % or 30 % of the glass composition, the larger Ca<sup>2+</sup> ions increase to much more than that required to be housed in the interstitial vacancies. To house the excess of such large cations more vacancies will be formed in the percolation channels of the leaching solution. This means easier penetration of the solution inside the glass matrix causing the observed deterioration in the glass durability. These results were confirmed by analyzing the glass composition after being immersed for 312 hours in different acids. It was found that the most durable glass was obtained when the base soda lime glass contains 10 % iron slag. The results show that the glass durability considerably increased, where it became 97.75 % better when leached in

HCl solution i.e. the corrosion of the base glass was 8.9 % of its original weight when immersed in 1N HCl solution for 312 hours, which was reduced to 0.2 % when the glass contains 10 % slag. The same glass gave the best durability against nitric acid solution (1N HNO<sub>3</sub>), but the durability enhancement was less than that obtained in the hydrochloric acid case, where the increase in the glass durability is 77.8 %. The results also revealed that the durability of the base glass in nitric acid is much better than its durability in hydrochloric acid with the same normality. The results showed that the durability of the glass containing 20 or 30 % slag is deteriorates as a result of the inhomogeneity in the glass structure.

Nevertheless, density is one of the properties which can give an indication to the glass structure, where it is controlled by the free volume of the glass network and the masses of the ions in the glass composition. The increase of the glass density when the slag is added to the glass composition is ascribed to the compaction of the glass network due to the presence of Al ions in the fourfold position, and the strong housing of barium ions in the interstices, also the greater stability of SiO<sub>4</sub> groups. When the slag content exceeds 15 % the increase in the glass density is attributed to the replacement of ions with higher atomic weight.

The IR results of the variations of the chemical compositions of the soda lime glasses by replacing some of its Na<sub>2</sub>O-by BaO or MgO reveal only minor shifts of the absorption bands, with the major characteristic absorption bands remaining persistent. The formation of a new band at 1500–1750 cm<sup>-1</sup> for glass leached in HNO<sub>3</sub>, and the disappearance of the band at 2850–2950, which may be attributed to molecular water, leads us to expect that the mechanism of glass corrosion may include some sort of water diffusion in the case of leaching in HNO<sub>3</sub>. Alternatively the leaching by HCl solution seems to be due to a mechanism which may only involve ion exchange between H<sup>+</sup> and M<sup>+</sup> or M<sup>2+</sup> respectively. Studies of the glass surface by means of SEM and EDX are in agreement with these conclusions.

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