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STRESS –STRAIN DIAGRAM OF SELF-CONSOLIDATING CONCRETE SUBJECTED TO CHEMICAL ATTACK

Mohammed M. Salman[1] **Qais J. Frayyeh**[2] ***Luma A. Zghair**[1]

1) Civil Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq
2) Building and Construction Engineering Department, University of Technology Baghdad, Iraq

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Abstract: Self-consolidating concrete (SCC) is increasingly used in a number of concrete applications, some of which are highly susceptible to attack by sulfuric acid. This work aimed to study the resistance of a wide range of different SCCs to sulfuric attack. The main variables studied included binder material type (highly reactive materials), limestone powder and hybrid fibers in this work, compaction, L-box and V-hopper were performed for the new mixtures. In this study, the specimens were immersed in a solution of sulfuric acid at a concentration (0.5%) for up to 289 days after normal curing for 28 days. Laboratory results show that concrete containing pozzolanic material has reduced mechanical properties compared to a mixture containing only limestone powder. The study also showed that there was an improvement in the resistance of concrete to acid solutions when hybrid fibers were added to the concrete mix. From the stress graph, the strain at a given axial stress will be less than once the failure becomes more severe, it will become less rigid than immersing the specimen for six months.

Keywords: *SCC***,** *sulfuric acid***,** *hybrid fiber***,** *stress strain diagram***,** *compressive strength, mass loss*

1. Introduction

The negative impact of an acidic environment on the durability and physical properties of historic buildings and infrastructure is in the spotlight globally. It is clear that the degradation of building materials will lead to rapid deterioration of structures. Therefore, it is necessary to fully understand the mechanism of degradation. There is some research regarding the effect of sulfuric acid on the durability of concrete, do some lab tests. **Fan et al.** [1] In their laboratory studies, they used an acid level pH less than (5.6) to study the tensile properties of concrete. The laboratory results showed the following:

1. There is an increase in the modulus of elasticity and tensile strength of concrete at the beginning of exposure, but at the end of exposure (after 70 days) a decrease in their values was observed.

2. Shape of close stress-strain relationship curves for concrete samples in different damage states. They reported that, at the initial time exposure (less than 30 days), the ultimate strain at the peak stress increase and will decrease later on.

An experimental study was carried out by Zhang. et al. [2] on uniaxial tensile properties of

**Corresponding Author*: *lumaabdulganee@yahoo.com*

concrete exposed to acid rain. The test samples were completely submerged in the acid rain simulation. After exposure for a certain time, uniaxial tensile tests are performed on the concrete samples. The results show that the elastic modulus, tensile strength and maximum strain have a slight increase in the early stage, and as the process lengthens, the modulus of elasticity and tensile strength decrease, while maximum stress continues to increase. It has been found that compressive strength is more sensitive than tensile strength in aggressive media. **Hewayde, et al**. [3] investigated the combined impact of concrete mixture design parameters (cement and coarse aggregate content, and the w/c ratio) for concrete exposure to sulfuric acid solution. The test period was three months for concrete samples immersed in acid solutions with pH range from 1.0 to 3.0. The test was ended after two months for concrete samples immersed in acid solutions with pH values less than 0.6, at this point the concrete samples initiated losing coarse aggregates. In their work, they used cement content range from (310 -570) kg/m3, w/c ratio range from (0.25 – 0.5) and the coarse aggregates range from (745 – 1010) kg/m3. **Joorabchian** [4] investigated the effects of H2SO4 attack on concrete mixtures prepared with limestone powder and metakaolin at different replacement levels. He used three concentrations of sulfuric acid solutions (3%, 5% and 7 %) with a pH value of (1.3, 1.2 and 1.15) to examine the resistance of concrete samples for a period of two months. Change in strength, weight loss and visual assessment were measured to evaluate the performance of the deteriorated specimens. The results indicated that, increasing the percentage of metakaolin would improve the performance of concrete samples and this due to the influence of pore densification of the concrete micro structure by incorporating metakaolin which plays a significant role in protecting concrete. The result also indicated that, mixtures with ternary binders of ordinary Portland cement, metakaolin and limestone powder have shown a positive effect with respect to resistance to sulfuric acid attack (change in strength, weight loss and visual assessment). This is due to that, in addition to the effect of pore densification of the concrete micro structure, limestone powder plays an important role in increasing pH surrounding concrete, where it has the ability to interact with the solution of acid and thus reducing the impact of the acid. **Salhi et al** . [5] Study the influence of acids and sulfates on the durability of self-compacting concrete; an experimental procedure was used to evaluate the influence of sulphate and acidic media on the mechanical and microstructural properties of SCC. The two cements used are CEMIII-A-42.5 cement (60% slag) and CEMI-52.5 cement and three water/binder ratios (E/L = 0.32-0, 38-0.44). SCC samples were kept in three media, water (control), 5% H2SO4 and 5% Na2SO4. The measured properties are: Compression strength of bulk specimens at 30, 90 and 180 days and analysis by X-ray diffraction (XRD). These results show that blast furnace slag improves the durability of SCCs. **Özlem et al.** [6] investigated the effect of densification the pore structure of SCC by incorporating mineral admixtures (fly ash) with quartz powder to obtain lower permeability for sulphate ions. The results indicate that a low resistance to sulfuric acid attack induced by the negative effect of pore densification can create less space for the inlet stresses caused by the emission growth of relatively large gypsum crystals. They also reported that SCC with cement and limestone powder which have higher porosity refers to better performance under sulphuric acid conditions. **Sara et al**. [7] studied the performance of two SCCs made with conventional portland cement CEM I 52.5R or with grain-size optimized slag cement CEM II / B-S 52.5R that have undergone severe attack with sulfuric acid (pH 2)., They reported that the quantification of degradation due to mass loss or volume change of concrete is mainly influenced by the frequency of acid solution renewal in which the concrete is soaked and the mechanical brushing procedure used to remove the degraded layer. The attack of sulfuric acid at very low pH is strongly influenced by the precipitation of the gypsum crystals, which can produce a long period of inactivity and act as a self-protective layer limiting diffusion of acids inside the substrate.

The aim of the work is to study the effect of using different materials such as limestone powder, pozzolanic materials and the use of hybrid fibers in concrete mixtures on the stress - strain behavior of concrete models exposed to sulfuric acid solutions.

2. Experimental work

2.1. Materials

Ordinary Portland cement was used **IQS 5:1984**[8]. For all concrete mixes, the sand, coarse aggregate and water were 778 kg/m^3, 890 $kg/m^3$and 170l/m^3 respectively. Two types of pozolana materials were used silica fume (SF) and Attapulguite according to (ASTM C1240 - 03) [9], and **(ASTM 618-03) [10] respectively,** The Attapulguite clay, was ground by blowing technique, to reach a high specific surface. The The user's HRA has been by heating Attapulguite powder at 750°C with an immersion time of 1/2 hour and then allowed to cool. In addition limestone powder were used in this work. The properties for the materials are listed in Table (1).

Table 1. The chemical and physical properties for the materials

Oxides	**cement**	**silica fume**	**Attapulguite**	Limestone powder	
				gubra	**chalk powde**
SiO_2	18.79	96.68	47.91	1.5	2.24
Fe_2O_3	3.9	0.069	1.81	0.08	0.12
Al_2O_3	4.5	0.20	20.94	0.32	0.42
CaO	66.57	0.54	10.06	54.6	68.73
MgO	3.57	0.12	6.18	0.27	0.70
SO_3	2.24	0.61	Nil	<0.07	<0.07
specific gravity	3.2	2.13	2.4	2.48	2.42
specific surface area m^2/g	4.37	15.7	2.1	2.1	3.17

The results of the fresh concrete were compared depending on the requirements of the fresh concrete for SCC[11]&[12].Different types of fibers were used , crimped plastic ,straight micro-reinforcement and polypropylene fibers , the aspect ratio were 63, 75 and 66.7 respectively . Table (2) shows the Sets and description of mixes Table (3) shows the mixtures that were used in this research.

Table 2. Sets and description of mixes

R SCC	**Mix with 100% cement as a Reference**
SCC LP	Mix with 70% cement and 30% limestone powder (chalk powder)
SCC G	Mix with 70% cement and 30% Gubra
SCC LP AT	Mix with 70% cementitiuos (10% Attapulgite of the weight of the cement) and 30% limestone powder (chalk powder)
SCC	Mix with 70% cementitiuos (10% SF by weight of the cement) and 30% limestone powder

LP SF	(chalk powder)
SCC LP SF HR1	Mix with 70% cementitiuos (10% SF by weight of the cement) and 30% limestone powder (chalk powder) and 0 .5% fibers by vol. of the mix (0.2 PP +0.3 St)
SCC LP SF HR2	Mix with 70% cementitiuos (10% SF by weight of the cement) and 30% limestone powder (chalk powder) % and 0 .5% fibers by vol. of the mix (0.2 PL +0.3 St)

Table 3. The SCC mixes

Mix notation	Mix NO.	cement kg/m^3	Attapulguite	silica fume kg/m^3	Limestone powder kg/m^3		SP% wt. of cement	Fibers by volume %		
					gubra	chalk powder		ST	PL	PP
RSCC	M1	500	-	-			7	-	-	-
SCC G	M2	350	-	-	150		3	-	-	-
SCC LP	M3	350	-	-		150	7.3	-	-	-
SCC LP AT	M4	315	35	-		150	9.3	-	-	-
SCC LP SF	M5	315	-	35		150	8.7	-	-	-
SCC LP SFHR1	M6	315	-	35		150	11	0.3	-	0.2
SCC LP SFHR2	M7	315	-	35		150	13	0.3	0.2	-

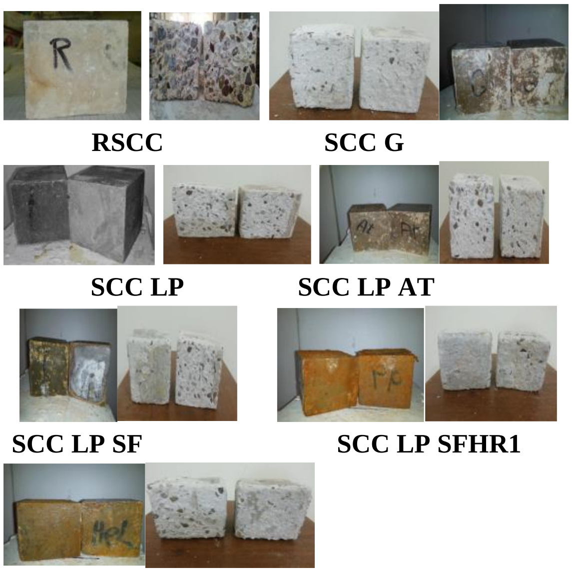
2.2. Preparation of Acid Solution

In this study, a chemical immersion test was conducted to evaluate the durability of SCC. Concrete samples were cured in water for 28 days and then immersed in an acidic solution. The initial pH (2.3) of the solution rose rapidly.. After the sample was completely soaked for 41 weeks, it was chemically soaked to dry the concrete sample at room temperature. Each mix group had its own acid bath. Figure (1). This is to provide a similar acidic environment for different binder mixes in each group of mixes.

Figure 1. Acid bath for concrete mixtures

2.3. Visual Inspection of Different SCC Mix Immersion in Sulfuric Acid Solution

During the test, samples were regularly removed from the acid solution for visual inspection. It was observed that with continued exposure, the surface color gradually changed from gray to off-white, or from yellow to white, and finally off-white, depending on the type of additive used. Honeycomb cavities were formed, the mortar surface was peeled off, and coarse aggregate was exposed. It was observed that damage began at the corners of the sample and the sample loosened and gradually powdered. After 30 days, the specimens particularly with silica were significantly discolored, with yellow as shown in Fig. (2). This may be attributed to the effect of sulfuric acid on the surface of the specimen before diffusion of the acid to the inner part of the specimens Finally, it was also observed that all concretes specimens kept their cubic forms but their dimensions decreased considerably. For example, the RSCC concrete specimens lost 2 to 3 mm on all sides



RSCC **SCC G**

SCC LP **SCC LP AT**

SCC LP SF **SCC LP SFHR1**

SCC LP SFHR2

Figure 2. Visual Inspection of Different SCC

3. Result and Discussion

3.1. Compressive Strength Tests

Table (4) and Figure (3) represent the results of compressive strength.

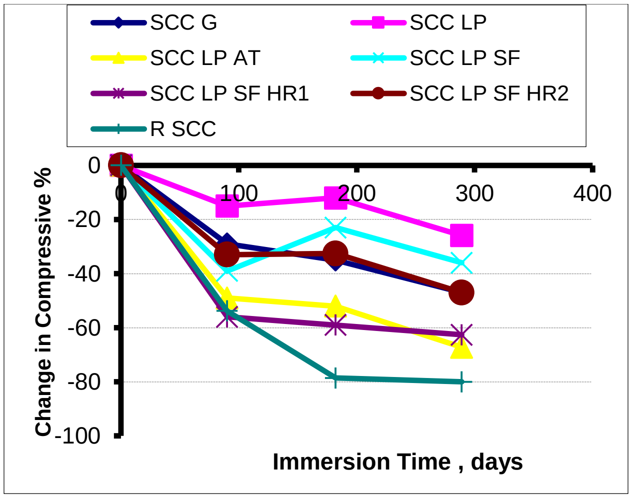


Figure 3. Relative change of compressive strength

Table 4. Compressive Strengths of Concrete Mixes

Mix notation	Mix NO.	Compressive strength 28 days before immersion (MPa)	Compressive strength after immersion (MPa)		
			90 days	182 days	289 days
RSCC	M1	72.0	21.0	16.4	15.7
SCC G	M2	45.5	32.0	29.5	24.1
SCC LP	M3	45.0	38.0	34.5	33.4
SCC LP AT	M4	51.0	26.0	20.0	16.8
SCC LP SF	M5	69.0	41.5	53.0	44.1
SCC LP SFHR1	M6	68.5	30.0	28.0	25.6
SCC LP SFHR2	M7	67.5	45.0	45.5	35.6

From figure (1), R SCC (high cement content) has been observed to show a significant decrease in strength at the end of the test. The reason for this anomaly is mainly due to the fact that the volume fraction of concrete made only of cement was higher than that of concrete made of cement and other mixtures because the acid attacks only cement. Due to. The loss of compressive strength at higher cement contents (500 kg / m3) was greater than that of mixtures with cement contents (350 and 315) kg / m3.This finding is supported by **Hewayde, et al.** [3] From Figure (3) ,concrete mixtures containing pozzolanic materials, which are represented by mixture No. 4 and 5, have a high compressive loss. This may be due to less C-H reacting with the acid

$CaSiO2.\ 2H2O + H2SO4 \rightarrow CaSO4 + Si\ (OH)\ 4 + H2O$ ……………. 1

These results are in agreement with the researchers' findings **Joorabchian** [4] and Senhadji **et al.** [13]. Mixtures with limestone powder only, have the lowest loss in strength This is due to: [13]

1. The higher fineness of the chalk powder has a positive effect on the resistance of SCC to acidic solutions. It fills the micro pores of the cement paste and the ability of the mortar to resist attack by sulfuric acid is enhanced by reduced permeability and porosity.

2. The presence of high calcium carbonate ($CaCO_3$) content (68.73%) has an effect on the ability of consuming more acid by limestone powder and as the proportion of cement decreases, (C-H) content decreases.

3.2. Static Modulus of Elasticity

The static modulus of elasticity is defined as the secant in the stress-strain curve at the point corresponding to 40% of the maximum strength [14]. The static modulus of elasticity was measured in compliance with ASTM C 469[15]. To avoid the damage of the testing device and their parts, all specimens were tested up to (0.4 f*c*) i.e stress strain curve was drown up to (0.4 f*c*). Table (5) and Fig. (4) Shows the result of this test. From Fig.(2), it is shown that in the initial damage stage, (182) days, the elastic modulus of concrete increases. For SCC concrete mixes (except for RSCC) Holschemacher and Klug [16] reported that modulus of elasticity of SCC can be increased with reducing the porosity. In the present work, this increase may be due to the formation of new chemicals compound with the concrete mass due to reaction between the acid and the cement paste, these new compound can fill the void, as a result, elastic modulus of concrete increases. When the damage continues, the elastic modulus of the specimen gradually decreases. This may be due to the effect of the expansion of these compound which can form voids and cracks, as a result, elastic modulus of concrete increases and this finding is supported by Fan et al [1] .It is also observed that hybrid fibers enhanced the resistance to sulfuric acid, The reduction was lesser in Ec comparable with compared to non-fiber blends mixtures.

Table 5. static modulus of elasticity of concrete mixes

Mix notation	**Mix NO.**	**Static modulus of elasticity, 28 days before immersion (GPa)**	**Static modulus of elasticity after immersion (GPa)**	
			182 days	**289 days**
RSCC	**M1**	**47.64**	**35.8**	**10.00**
SCC G	**M2**	**23.68**	**54.29**	**15.08**
SCC LP	**M3**	**35.29**	**43.00**	**25.19**
SCC LP AT	**M4**	**38.13**	**25.9**	**29.76**
SCC LP SF	**M5**	**42.46**	**61**	**24.2**
SCC LP SFHR1	**M6**	**45.89**	**34.5**	**39.5**
SCC LP SFHR2	**M7**	**47.48**	**51.8**	**33.23**

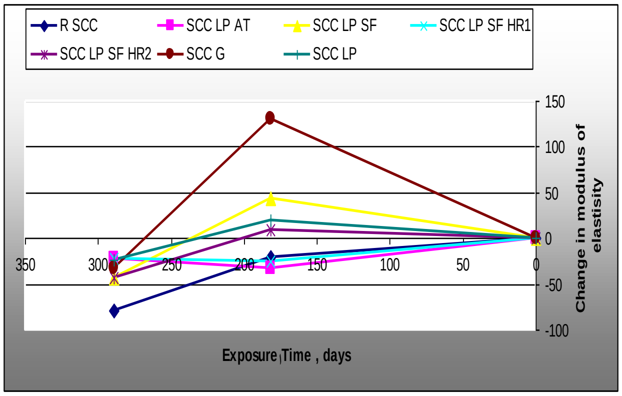


Figure 4. The relative change of static modulus of elasticity

3.3. Stress-Strain Behavior

The stress – strain diagram before chemical immersion for all concrete mixes is plotted in Fig. (3). Mixtures containing hybrid fibers have been observed to have a gradual increase in elongation compared to plain concrete, indicating higher elongation absorption capacity. [17]

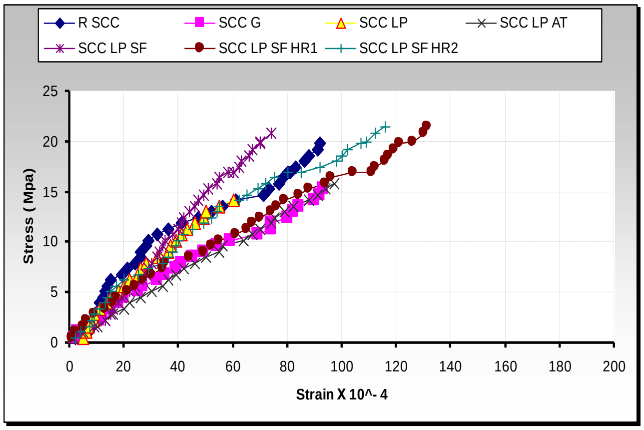


Figure 5. Stress – strain relationship before chemical immersion for all SCC concrete mixes

Fig. (6) to (12) shows stress-strain curve for all concrete mixes under different immersion time. In the present work, after 182 days exposure, the strain at a given imposed axial stress is lower, in this stage, the concrete will become a little more brittle at the initial damage period. (182 days) comparable with specimen at normal curing. However, once the damage becomes more severe, it will become more ductile comparable with specimen immersion for 182 days, This behavior may be attributed to that, At the initial exposure, the continuation of chemical reactions between the cement components and acid leads to reduced porosity and make the concrete more brittle

After 289 days exposure to H_2SO_4 As the damage became more sever, the porosity will increase, the concrete in this stage will became ductile.

Except for reference concrete (RSCC) , because of the use of a high proportion of cement and the absence of limestone powder , the damage of the specimens was more sever comparable with other concrete specimens contain limestone powder , Porosity may be increased since the beginning of exposure , as a result , makes concrete more ductility at the initial and final damage period. (90 and 289 days) as shown in Fig (12)

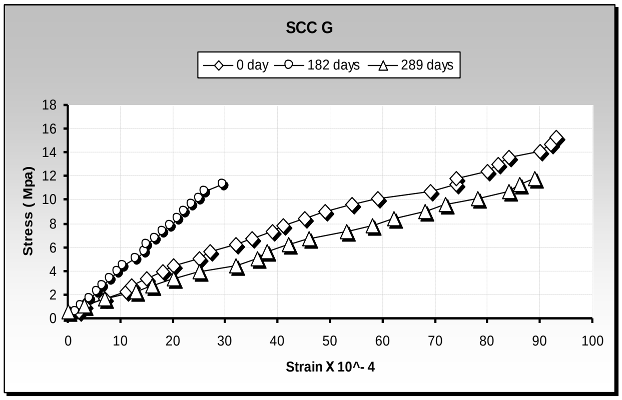


Figure 6. Stress – strain relationship for SCC G concrete mixes

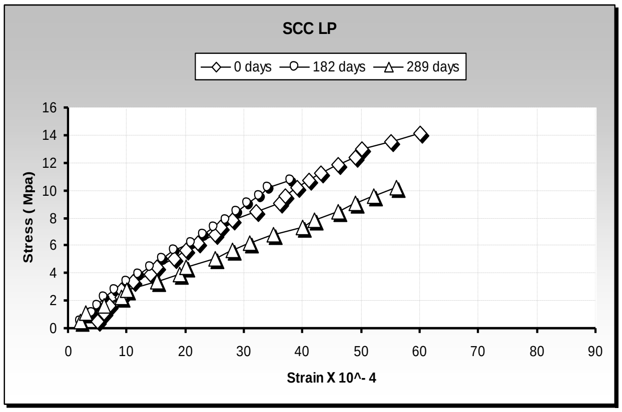


Figure 7. Stress – strain relationship for SCC LP concrete

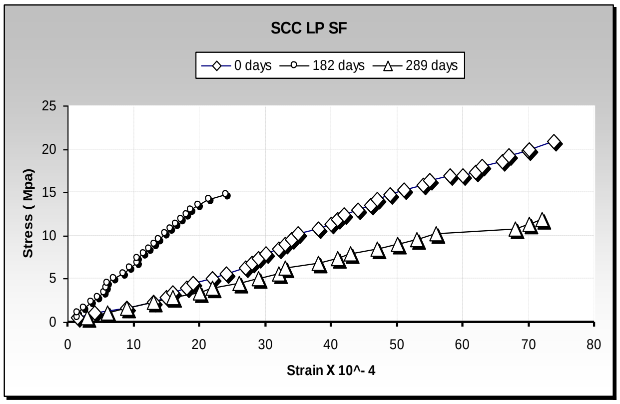


Figure 8. Stress – strain relationship for SCC LP SF concrete mixes

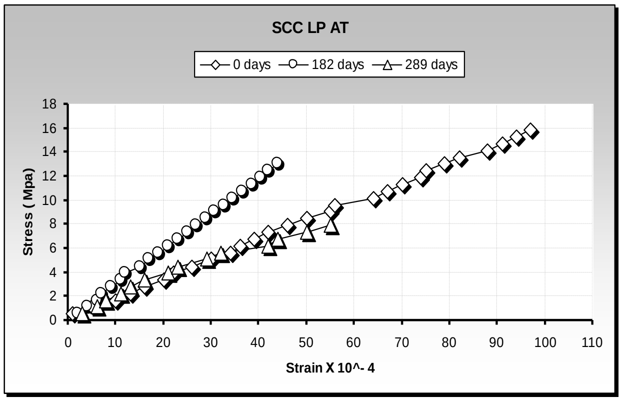


Figure 9. Stress – strain relationship for SCC LP AT concrete mixes

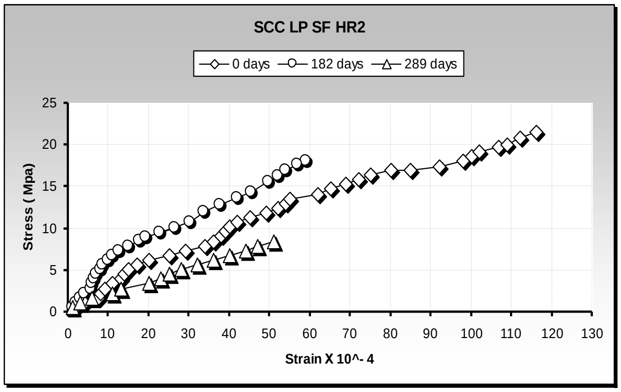


Figure 10. Stress – strain relationship for SCC LP SF HR2 concrete mixes

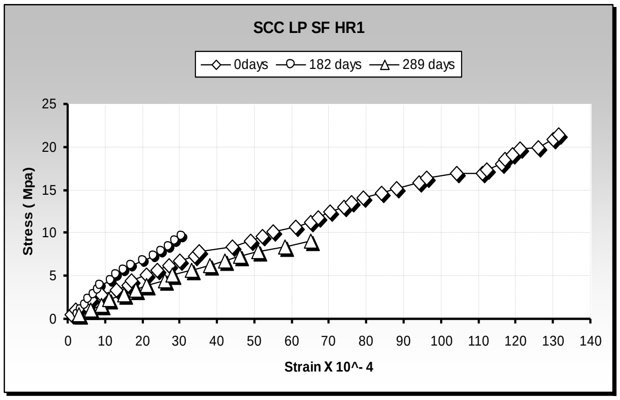


Figure 11. Stress – strain relationship for SCC LP SF HR1 concrete mixes

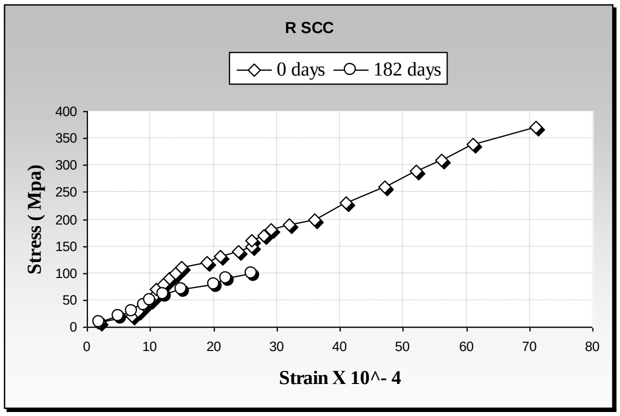


Figure 12. Stress – strain relationship for R SCC concrete mixes

5. Conclusion

1. SCC Concrete in general deteriorates when exposed to acid attack, but in varying proportions depending on the quality of the additives.

2. Mixes with high cement content (RSCC) has the highest loss of mechanical properties at the end of the test comparable with mixes containing different mineral admixtures.
3. Concrete with silica fume (M5, M6, and M7) has a significantly reduced compressive strength by (36, 63, 47) %, respectively, comparable to M3. The reduction was 26%. M4 (with HRA) also has a high compressive strength loss rate, comparable to other compounds without HRA (M3). The reduction was 67%.
4. The mixture with powdered limestone (chalk powder) (M3) had the least loss of compressive strength. The reduction was 26%. On the other hand, blending with (Gubra) has a negative effect on compressive strength
5. In the case of using hybrid fibers there is a gradual increase in strain when compared to plain and this indicate more strain absorbing capacity
6. After 182 days' exposure, from the stress strain diagram the strain at a given imposed axial stress is lower once the damage becomes more severe, it will become more less stiffness comparable with specimen immersion for 182 days

Conflict of interest

The authors confirm that the publication of this article causes con conflict of interest.

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