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Behavior of rigid pavements containing recycled concrete aggregate exposed to magnesium sulfates attack

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ABSTRACT

The concept of sustainability has gradually expanded within engineering fields, mainly due to its role in conserving natural raw materials by replacing them with recycled materials. One practical example is the replacement of natural aggregate with recycled concrete aggregate (RCA) in rigid pavements, which helps reduce waste. However, the performance of RCA under varying environmental conditions remains unclear and requires extensive research. The study aims to examine the effect of external sulfate attack on concrete mixes containing different proportions of recycled concrete aggregate and silica fume. This study partially replaced natural coarse aggregate with recycled coarse aggregate at ratios of 50%, 75%, and 100%, and cement was partially replaced with 10% silica fume. Four mixes were prepared, including a Control mix (C), (A1) mix, (A2) mix, and (A3) mix. Workability was measured through a slump test, followed by casting 48 cubes with dimensions of 15 cm. Half of the cubes (24) were immersed in water, while the other half were placed in water and 5% magnesium sulfate solution for 28 and 120 days. Density and compressive strength tests were conducted on all samples at these curing durations. The study compared the results of samples immersed in water with those submerged in the water and magnesium sulfate solution to determine the degree of sulfate impact. Results showed that silica fume positively affected sulfate resistance and significantly improved RCA mixes in the later ages. Nonetheless, the control mixes exhibited greater strength than the RCA mixes, particularly the (A3) mix. The role of silica fume was evident from the results, and the study also highlighted the performance of recycled aggregate under external sulfate attack in specific terms.

Keywords: concrete pavement, recycled coarse concrete aggregate, sustainability, silica fume, external sulfate attack, sulfate solution.

INTRODUCTION

Due to its durability and capacity to withstand substantial loads, rigid pavement has seen a rise in global demand for road construction. The maintenance needs for rigid pavement are inferior to those of asphalt pavement. The rigid pavement layer effectively distributes vehicular loads, alleviating stress on underlying layers and extending the road's durability. Rigid pavements incur a more significant initial construction cost compared to asphalt pavements. One potential cause could be material costs, given the potential for price volatility or production capacity constraints in Iraq (Khalid and Abbas, 2023; Tarrad and Abbas, 2023). This compels us to seek more economical options while maintaining the quality of fundamental elements. Concrete is an essential component of rigid pavement, encompassing many types, such as reinforced concrete, standard concrete, and pre-stressed concrete. Cement is regarded as a fundamental element that determines the strength of concrete. The taking out and production of the cement adversely affect the environment. The method used to produce cement creates carbon emissions that account for 8% of global carbon dioxide emissions, posing significant environmental issues. Researchers have identified multiple alternatives to reduce the cement content in concrete, with silica fume proving particularly effective. Research has demonstrated that incorporating silica fume into concrete improves its performance by augmenting flexural and compressive strength (Rout et al., 2023). These strengths increase when silica is used in place of cement; the ideal combination of silica with metakaolin yields the highest compressive strength. An inexpensive and effective alternative to metakaolin is silica fume (Devi and Magandeep, 2020).

Incorporating silica fume and tire rubber additives improves concrete’s load-bearing capacity by strengthening its flexibility and strength (Liu et al., 2019). Several circumstances may influence the ideal combination of concrete constituents. One of these parameters is the water-to-cement ratio. Incorporating silica fume can alter this ratio and enhance the concrete’s strength (Devi and Magandeep, 2020). Incrementally incorporating silica fume increases cement cohesiveness by up to 40%. Incorporating silica fume at a 10% to 15% ratio results in optimal compressive and flexural strength values (Amudhavalli and Mathew, 2020).

By reducing waste and providing economic benefits, recycled concrete aggregate is a substitute for natural aggregate, preserving natural resources and mitigating environmental consequences (Xinget al., 2022). Nonetheless, the application of RCA may yield adverse consequences. The strength rapidly deteriorates under both static and dynamic loads (Allujami et al., 2022; Khalid and Abbas, 2023). The inherent quality of the original concrete and the crushing process affect the mechanical attributes of RCA. Recycling aggregate influences physical properties such as water absorption and porosity. Researchers recommend incorporating silica fume to diminish water absorption and enhance compressive strength, particularly at a concentration of 10% (Marie and Mujalli, 2019; Berredjem et al., 2020; Çakır and Sofyanlı, 2015; Hasan and Al-Shamaa, 2018; Al-Billbassi and Al-Shamaa, 2020).

The surrounding environment and microclimate significantly influence concrete durability, necessitating suitable elements and exact combination proportions for lasting sustainability. The durability of concrete is defined by its ability to endure weathering, chemical attack, and abrasion (ACI CT-13; ACI 201.2R-01). Salts in soil, groundwater, and industrial sources significantly affect concrete via chloride penetration, efflorescence, and sulfate attacks. Sulfates cause expansive compounds in concrete, leading to cracks and degradation (ACI CODE-318-19). Compared to other sulfate types, the samples subjected to magnesium salts displayed the most pronounced expansion and considerable cracking, while the sodium salt samples showed less deterioration. Furthermore, magnesium sulfates ($MgSO_4$), a particularly detrimental variant of sulfate, can engage with all hydrated cement components (Khan and Abbas, 2021). The reaction process is shown by the Equation (1) (Drimalas et al., 2010):

$$\begin{aligned} &3\ \mathrm{CaO{\cdot}2\ SiO_2} + \mathrm{Mg}\overline{\mathrm{S}}\mathrm{H_7} \\ &\rightarrow 3\ (\mathrm{C}\overline{\mathrm{S}}\mathrm{H_2}) + 3\ \mathrm{Mg\ (OH)_2} + 2\ \mathrm{S} \end{aligned} \tag{1}$$

Three testing methods examined the impact of external sulfate exposure on seawater: full submersion in a (5%) $Na_2SO_4{\cdot}10H_2O$ solution, immersion cycles, and drying at temperatures. Sample C1 contains 12.5% dredged fine sediments, and sample C2 contains 20% dredged fine sediments. The results revealed that C1 displayed enhanced resistance to sulfate attack, but C2 showed heightened porosity. The accelerated drying cycles were at 60 °C and 105 °C. The finder expansive products cause considerable degradation of the samples (Achour et al., 2019). This research aims to compare the performance of rigid pavements before and after exposure to external sulfate attack for standard mixtures and mixtures containing (silica fume and different percentages of recycled coarse concrete aggregate). Additionally, to assess the effect of silica fume on the resistance to external sulfates and the durability of rigid pavements in the mixtures containing recycled coarse concrete aggregate.

EXPERIMENTAL PROGRAM

Materials properties

Sulfate-resistant Portland cement type (V):

Table 1 displays cement‘s physical and chemical characteristics following the Standard (ASTM C150/C150M-21).

Coarse aggregate (CA)

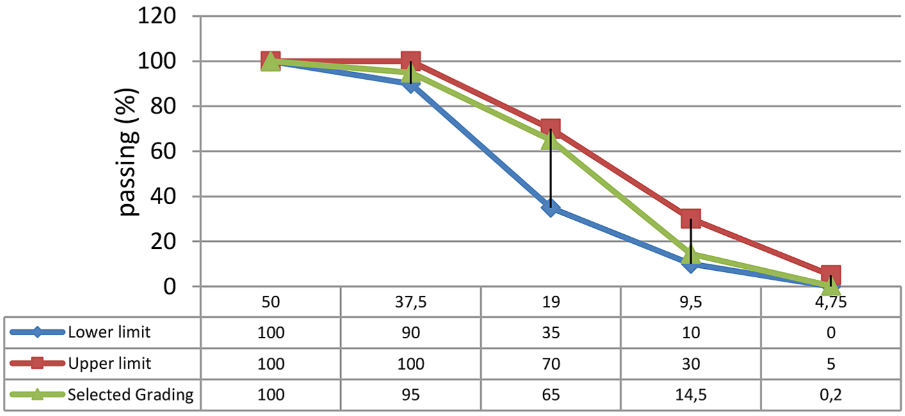
According to the Iraqi Specification (SCRB-Standards/R10-2003), Figure 1 illustrates the gradation of coarse aggregate. At the same time, the physical parameters are detailed in Table 2 following the Specification (ASTM C33/C33M-16).

Fine aggregate (FA)

According to the Iraqi Specification (SCRB-Standards/R10-2003), Figure 2 illustrates the gradation of fine aggregate. At the same time, the physical parameters are detailed in Table 2 following the Specification (ASTM C33/C33M-16).

Table 1. Sulfates resistance of Portland cement properties

Test		Result	(I.Q.S. No.5-1984) 42.5SR	(ASTM C150 / C150M-20)
Physical properties	Fineness, specific surface by air-permeability apparatus, m^2/kg	345	300 Min.	260 Min.
	Initial Setting Time, hr: Min	01:40	00:45 Min.	00:45 Min.
	Final Setting Time, hr: Min	03:00	10:00 Max.	6:15 Max.
	Autoclave expansion %	0.040	0.8 Max.	0.8 Max.
	Compressive strength, MPa			
	3 days	30	--	8 Min
	7 days	35	--	15 Min.
	28 days	48	42.5 Min.	21 min
Chemical properties	Silicon oxide SiO_2, (%)	20.27	--	--
	Aluminium oxide AL_2O_3, (%)	4.17	--	--
	Ferric oxide Fe_2O_3, (%)	5.6	--	--
	Calcium oxide CaO, %	60.60	--	--
	Magnesium oxide (MgO), %	3.2	5 Max.	6 Max.
	SO_3 %	1.4	2.5 Max. for $C_3A < 3.5\%$	2.3 Max. for $C_3A < 8\%$
	(C_3A), %	3	--	5 Max
	Insoluble residue (I.R.), %	0.8	1.5 Max.	1.5 Max.
	Loss On Ignition (L.O.I.), %	2.7	4 Max.	3 Max.



	50	37,5	19	9,5	4,75
Lower limit	100	90	35	10	0
Upper limit	100	100	70	30	5
Selected Grading	100	95	65	14,5	0,2

Figure 1. Coarse aggregate gradation

Recycled concrete coarse aggregate (RCA)

According to the Iraqi Specification (SCRB-Standards/R10-2003), Figure 3 illustrates the gradation of RCA. At the same time, the physical parameters are detailed in Table 2 following the Specification (ASTM C33/C33M-16). Figure 4 shows recycled concrete aggregate.

Water

The drinking water in Baghdad is utilized for both casting and curing processes.

Table 2. Properties of RCA, fine aggregate, and natural aggregate

Aggregate properties	Bulk specific gravity	Apparent specific gravity	Percent water absorption	Los Angeles Abrasion, %
FA	2.54	2.6	0.3	----
CA	2.58	2.86	0.5	15.26
RCA	2.4	2.53	0.8	32

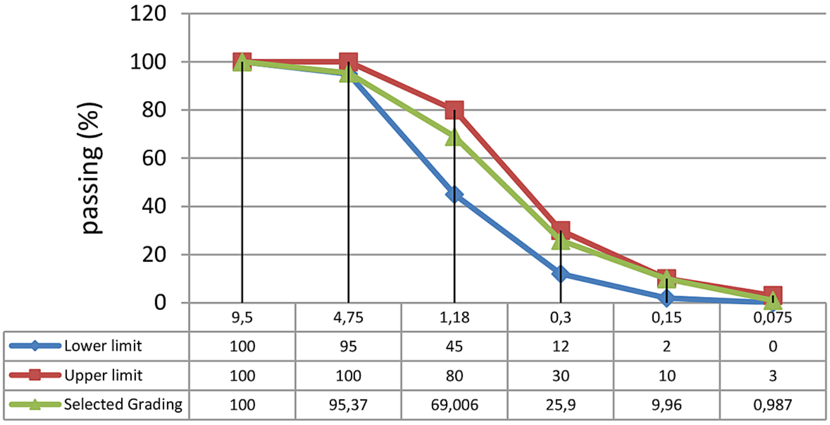


Figure 2. Fine aggregate gradation

Silica fume (SF)

The silica fume employed conformed to the (ASTM-C1240) standard. SF is used as a replacement for cement. Table 3 presents the standard properties; Table 4 outlines the chemical and physical specifications.

Table 3. Properties of SF

Properties	Test value
Color	Grey/medium grey
State	Amorphous sub-micron powder
Bulk density	500–700 kg/m^2
Specific gravity	2.1–2.4

Proportions of the mixture

After immersing the recycled coarse aggregate in water for 2 to 3 hours, completely dry its surface. According to the (ACI PRC-325.9-15) specification, the mix was designed with a compressive strength of 35 MPa. Four mixes were designed: the Control mix (C), mix (A1) containing 50% RCA + 10% SF, mix (A2) containing 75% RCA + 10% SF, and mix (A3) containing 100% RCA + 10% SF. The reference mix's water-to-cement ratio (w/c = 0.408) varies depending on the silica fume and RCA replacement ratios. 315 kg/m^3 of cement was used in these mixes with a partial replacement ratio (10%) of silica fume.

Figure 4. RCA-made of crushing concrete

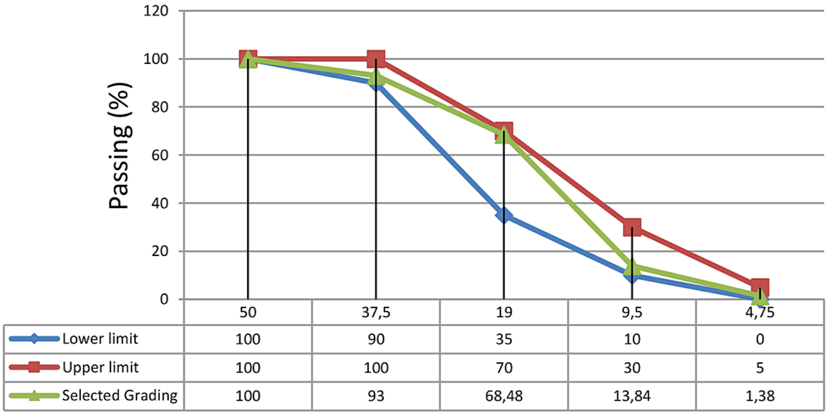


Figure 3. RCA gradation

Samples preparation and curing

Following the main objective of this research, 48 concrete cubes measuring 150 mm were produced to assess their compressive strength. A nylon mattress was placed over the cubes at room temperature to prevent moisture loss through the molds. Twenty-four hours afterward, cubes can be immersed in water to facilitate curing. After twenty-eight days, twenty-four cubes were removed from the water and magnesium salts ($MgSO_4$) at a weight ratio of 5%. This study was embraced by many investigators, such as (Drimalas et al., 2010; Achour et al., 2019; Najmabadi, 2018). This was conducted to replicate the sulfate attack procedure following [ASTM C88 C88M-13] and [ASTM C1012/C1012M-09] standards. For 28 and 120 days, the cubes were exposed to exterior salts, replenishing the solution every four weeks. The solution was applied thoroughly, encompassing all facets and faces of the samples (Khan and Abbas,2021), as illustrated in Figure 5. The other cubes were concurrently immersed in water for specific periods.

TEST METHODS AND RESULTS

Slump test

The workability of concrete is evaluated using a slump test, which ensures that the mixture meets its original purpose without segregation or excessive bleeding. According to the specification, the slump test value is at most 5 cm, (SCRB/R10-03(07)). Table 5 presents the results of the test for the four mixtures:

Table 4. Chemical and physical requirements of SF

Physical properties	Test results	ASTM C-1240 specification
Percent retained on 45 µm (No.325) sieve	6	≤ 10
Accelerated pozzolanic strength activity index with Portland cement at seven days	119	≥ 105
Specific surface m^2/kg	15432	≥ 15000
Oxide composition	Test results	ASTM C-1240specification
SiO_2 %	93.77	≥ 85
Moisture content %	0.36	≤ 3.0
Loss on ignition %	1.62	≤ 6.0

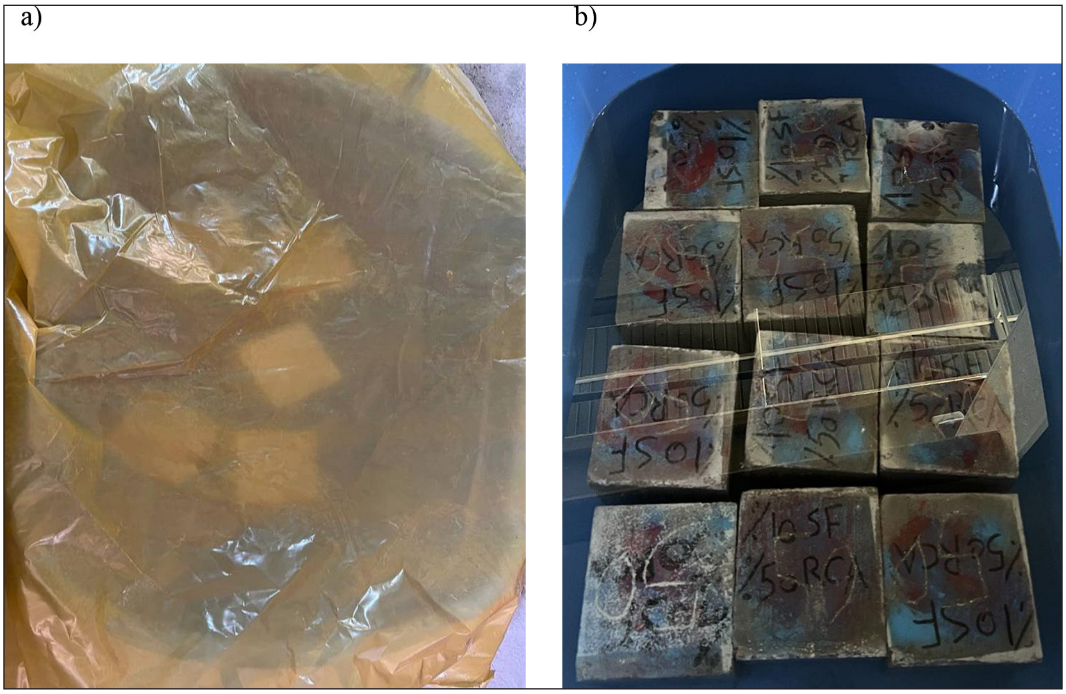


Figure 5. Concrete specimens submerged in a container filled with $MgSO_4$ solution: (a) closed container, (b) open container

Table 5. Slump test results

RCA%	0%	50%	75%	100%
Slump (mm)	50	45	37	30

There is an opposite relationship between the percentage of RCA replacement and the slump rate. We can observe that the slump in the control mix (C) was 50 mm, while the slump in the blend (A1) containing 100% RCA was 30 mm. We notice that the reduction percentage between the two mixes was 40%. When comparing the control mix (C) with the mix (A2) containing 50% RCA, it was found that the percentage decreased to 10%. As for mix A3, which includes 75% RCA, the slump reduction percentage compared to the control mix (C) was 26%. The presence of silica fume and RCA was one of the main factors in changing the slump values. In line with (Tang et al., 2016; Kapoor et al., 2020; Tran et al., 2021), RCA's rough texture (which increases friction between particles) and its high water absorption reduce the workability of the mixes. Conversely, silica fume reacts with cement to generate additional calcium silicate hydrates (C-S-H), making the mix denser. As indicated by (Jagan and Neelakantan, 2021; Al-Hindawi et al., 2023), silica fumes have a large surface area, increasing water absorption and reducing workability.

Density

Following the standard [ASTM C 642-97], the density test was performed on all water-treated samples cured to a magnesium sulfate and water solution (5% $MgSO_4$ + water) at 28 and 120 days, as shown in Table 6.

As shown in Table 5, the control mix (C) density increased to 2.325 g/cm³ at twenty-eight days and up to 2.4 g/cm³ at 120 days. Conversely, the RCA mixes (A1, A2, A3) have a lower density than the control mix (C) at 28 and 120 days. Since RCA mixes have a lower density, according to studies (Berredjem et al., 2020; Verian, 2012). The mixture A3 was the least dense. Research has proven that mixtures containing 100% RCA are the weakest in density (McNeil and Kang, 2013; Thomas et al., 2018; Al-Mulla et al, 2020; Al-Shamaa et al, 2024). When comparing the control mix with the A3 mix, the reduction was 16.215% at 28 days and 15.4% at 120 days for the samples cured with water. The samples exposed to external sulfate attack showed a density reduction percentage for A3 samples compared to control samples of 18.47% at 28 days and 18.3% at 120 days, as shown in Figure 6.

Compressive strength test

The compressive strength test determines concrete's bearing capacity and characteristics according to the standard specification [BS EN 12390-3]. As depicted in Figure 7, the test was performed using the ELE International hydraulic press device. Three samples were analyzed for each mixture and age according to the standard [BS EN 12390-1]. The samples underwent uniaxial pressure. Figure 8 shows samples before and after the testing. Table 7 shows the compression test results performed at 28 and 120 days.

The results shown in Figure 9 indicate that the RCA mixes (A1, A2, A3) demonstrated reduced strength compared to the control mix (C), regardless of whether the samples were water-cured or exposed to external sulfate attack, which

Table 6. Density of concrete samples (g/cm³)

Types of mix	Time (days)	Density of samples cured with water (g/cm³)	Density of samples exposed to external sulfate attack (g/cm³)
(C)	28	2.325	2.285
	120	2.4	2.382
(A1)	28	2.287	2.2
	120	2.376	2.289
(A2)	28	2.212	2.12
	120	2.3	2.207
(A3)	28	1.948	1.863
	120	2.03	1.946

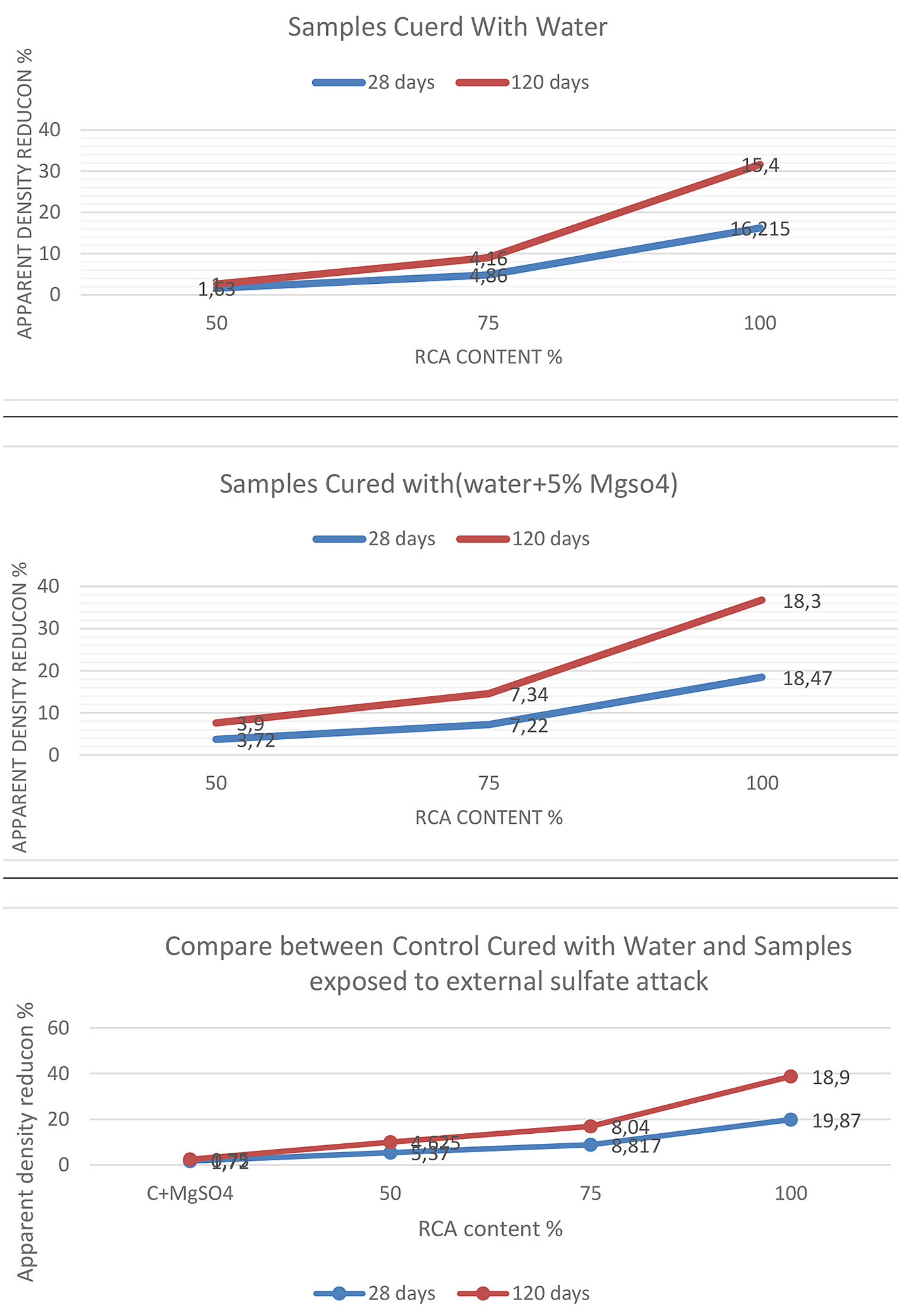


Figure 6. Density of concrete mixes

Table 7. Compressive strength (MPa)

Type of mix	Time (days)	Compression of samples cured with water (MPa)	Compression of samples exposed to external sulfate attack (MPa)
(C)	28	38.5	33.7
	120	55.5	50.24
(A1)	28	35.3	30.1
	120	52.66	48.2
(A2)	28	34	29
	120	49.77	45.96
(A3)	28	33.88	27.76
	120	46.78	42.12

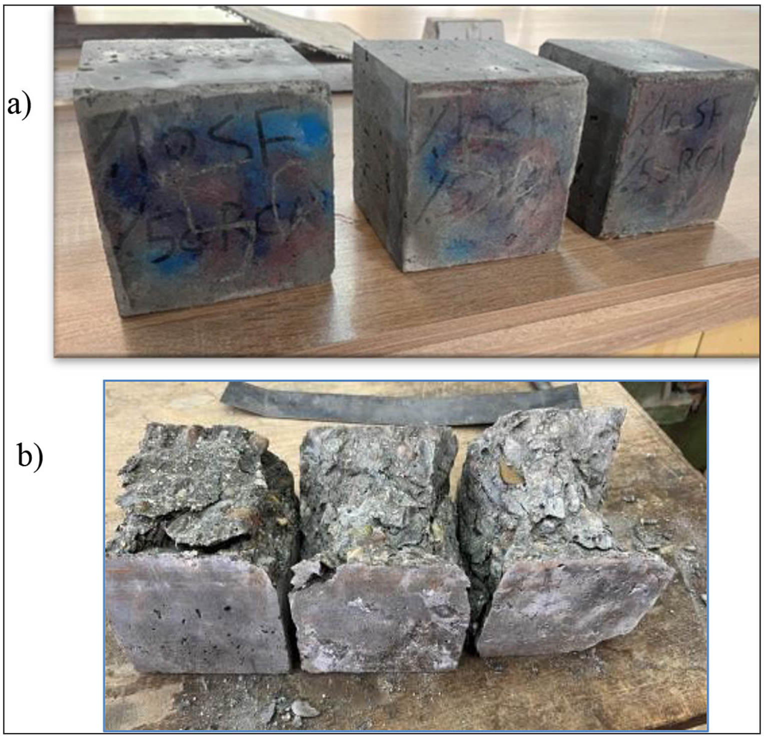


Figure 7. ELE for compressive strength test

is consistent with the results discussed by the researcher (Li et al., 2018), where mixtures containing replacement ratios of 20%, 50%, and 100% showed a decrease of 4.1%, 7.6%, and 13.1% at 28 days (Kapoor et al., 2020) supported this, as the compressive strength of the 50% mix decreased by 4.5% compared to the control mix in 28 days, while (lu et al., 2024) treated the samples containing 100% RCA and coated them with silica, then exposed them to salt attack at 28 days, there was a 15% decrease in the results compared to the samples containing natural aggregate. While the A1, A2, and A3 mixtures treated with water showed a decline of 7.79%, 11.68%, and 12% respectively over 28 days, the percentages were 5.117%, 10.32%, and 15.71% over 120 days when compared to the control mixture. This is due to the porosity and quality of the recycled concrete aggregate (RCA), which is considered weaker than that of natural aggregate (Xiao et al., 2005). External sulfate attacks intensified the degradation of RCA and heightened deterioration due to the porous characteristics of the RCA, facilitating deeper penetration of sulfate ions.in line with (Bonakdar and Mobasher, 2010; Sasanipour and Aslani, 2019), the incorporation of silica fume enhanced the strength of the RCA mixtures by refining the microstructure and mitigating long-term degradation, thus enhancing their resistance to external sulfate assault and diminishing porosity. The interaction between calcium hydroxide and silica fume generates supplementary calcium silicate hydrate (C-S-H), strengthening the bonding matrix and partially offsetting the strength reduction in RCA mixtures.

Figure 8. Samples (a) before and (b) after compressive testing

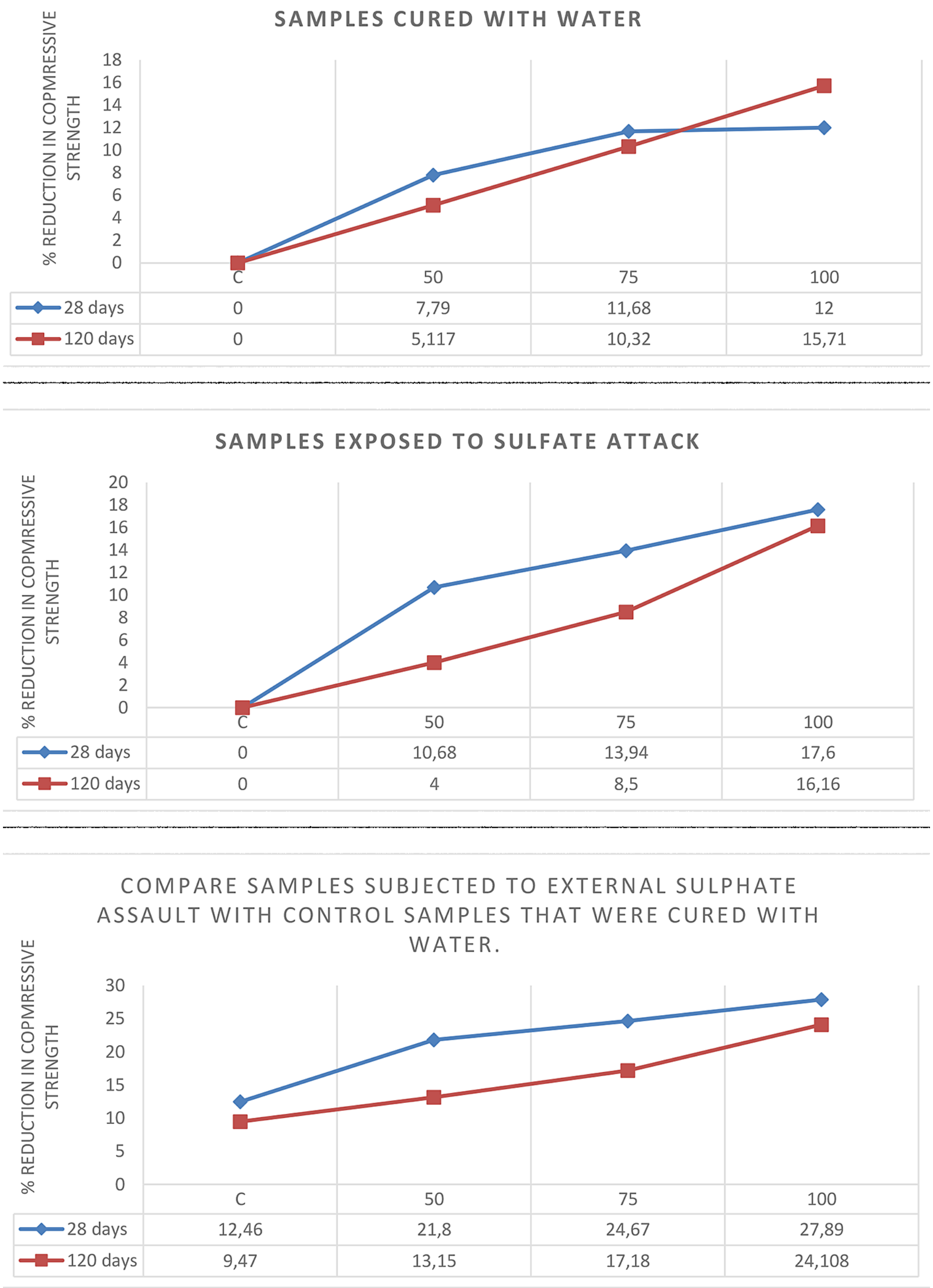


Figure 9. Compressive strength of concrete mixes

Table 8. Univariate analysis of variance – between-subjects factors

Between-subjects factors			
		Value label	N
Treatment	1.00	Water cured	8
	2.00	Exposure $MgSO_4$	8
Age	28.00	28 days	8
	120.00	120 days	8
Mix	1.00	Control	4
	2.00	A1	4
	3.00	A2	4
	4.00	A3	4

Table 9. Descriptive statistics

Treatment	Age	Mix	Mean	Std. deviation	N
Water cured	28 days	Control	38.5000	.	1
		A1	35.3000	.	1
		A2	34.0000	.	1
		A3	33.8800	.	1
		Total	35.4200	2.15165	4
	120 days	Control	55.5000	.	1
		A1	52.6600	.	1
		A2	49.7700	.	1
		A3	46.7800	.	1
		Total	51.1775	3.75059	4
	Total	Control	47.0000	12.02082	2
		A1	43.9800	12.27537	2
		A2	41.8850	11.15107	2
		A3	40.3300	9.12168	2
		Total	43.2988	8.88568	8
exposure_MgSO4	28 days	Control	33.7000	.	1
		A1	30.1000	.	1
		A2	29.0000	.	1
		A3	27.7600	.	1
		Total	30.1400	2.55859	4
	120 days	Control	50.2400	.	1
		A1	48.2000	.	1
		A2	45.9600	.	1
		A3	42.1200	.	1
		Total	46.6300	3.47783	4
	Total	Control	41.9700	11.69555	2
		A1	39.1500	12.79863	2
		A2	37.4800	11.99253	2
		A3	34.9400	10.15405	2
		Total	38.3850	9.25639	8
Total	28 days	Control	36.1000	3.39411	2
		A1	32.7000	3.67696	2
		A2	31.5000	3.53553	2
		A3	30.8200	4.32749	2
		Total	32.7800	3.57141	8
	120 days	Control	52.8700	3.71938	2
		A1	50.4300	3.15370	2
		A2	47.8650	2.69408	2
		A3	44.4500	3.29512	2
		Total	48.9038	4.13774	8
	Total	Control	44.4850	10.10918	4
		A1	41.5650	10.61161	4
		A2	39.6825	9.79066	4
		A3	37.6350	8.47274	4
		Total	40.8419	9.12518	16

Note: dependent variable strength.

Table 10. Tests of between-subjects effects

Source	Type III sum of squares	df	Mean square	F	Sig.	Partial eta squared
Corrected model	1249.032[a]	15	83.269	.	.	1.000
Intercept	26688.940	1	26688.940	.	.	1.000
Treatment	96.580	1	96.580	.	.	1.000
Age	1039.901	1	1039.901	.	.	1.000
Mix	101.694	3	33.898	.	.	1.000
Treatment * Age	.537	1	.537	.	.	1.000
Treatment * Mix	.506	3	.169	.	.	1.000
Age * Mix	9.275	3	3.092	.	.	1.000
Treatment * Age * Mix	.540	3	.180	.	.	1.000
Error	.000	0	.			
Total	27937.973	16				
Corrected total	1249.032	15				
a. R squared = 1.000 (adjusted R Squared = .)						

Note: a. R squared = 1.000 (adjusted R squared =.). Dependent variable: strength.

The compressive strength data was statistically analyzed using the SPSS program and the three-way ANOVA method; the data was input as shown in Table 8. The results in Tables 9 and 10 indicate that the curing method significantly affected the strength, as exposure to external salt attacks negatively impacted the concrete's durability. On the other hand, age played an important role in improving the strength of concrete. The variation in mixes led to differences in resistance, with the control mix showing the best results. However, among the CRCA mixes, mix A1 was closest to the control mix and the best among the CRCA mixes.

CONCLUSIONS AND DISCUSSIONS

The slump rate decreased as the proportion of replacement with RCA increased, with the (A3) mixture exhibiting the least reduction. Compared to the control mix (C), a reduction rate of 40% was observed. The rationale for this is the heightened absorption of recycled aggregate and its rough texture, which results in augmented friction among the particles. The interaction of silica fumes with cement enhanced the mixture's density, hence diminishing workability.

Silica fume and RCA affect density, as a significant decrease in the density of RCA mixes was observed compared to the control mix (C) under both treatment conditions (water curing and exposure to external sulfate attack). The mix (A3), which consists of a complete 100% replacement of recycled concrete aggregate, showed the lowest density compared to the control mix. This is due to the high permeability of the recycled concrete aggregate. It has a low specific density and lower structural integrity than natural aggregate. However, silica fume contributed to reducing porosity, improving cohesion, and increasing the density of the mix.

All mixtures subjected to external sulfate attack exhibited a reduction in density relative to the water-treated combinations. Upon comparison of the density of the control mixture (C) subjected to water cure and external sulfate attack, a reduction of 1.72% was observed after 28 days and 0.75% after 120 days. Conversely, the RCA mixtures demonstrated a more significant susceptibility to external sulfate attack, as the (A3) mixture composed entirely of RCA displayed the lowest density performance, with a density reduction of 11.68% at 28 days and 12% at 120 days relative to the control mixture (C) subjected to external sulfate attack. Compared to the (A3) samples water cured, the density reduced by 4.36% after 28 days, then became 4.13% after four months.

The results showed a compressive strength of 38.5 MPa in 28 days and 55.5 MPa in 120 days for the control mix (C) cured with water. The results for the water-treated RCA mixtures decreased, with the A3 mixture giving the lowest compressive strength. The percentage decline in strength was 12% in 28 days and 15.71% in 120 days compared to the control mixture (C).

The compressive strength of the control mix (C) subjected to external sulfate attack significantly decreased compared to the water-cured control mix, exhibiting reductions of 12.46% at 28 days and 9.47% at 120 days. The RCA mixes subjected to external sulfate attack exhibited inferior strength relative to the control mix and the RCA mixes treated with water. The mix (A3) showed the most severe decrease among the RCA mixes relative to the control mix exposed to sulfate assault, with a strength reduction of 17.6% at 28 days and 16.16% at 120 days. Compared to the mix (A3) water treated, there was an 18.06% reduction after 28 days, and then after four months, it became 9.96%.

The advantages of silica fume were evident after 120 days; it enhanced the strength of mixes involving recycled concrete aggregate (RCA) while decreasing compressive strength and density with age. Silica fume effectively mitigates sulfate-induced damage. This reaction diminishes the permeability of concrete, reduces the concentration of $MgSO_4$, and improves its resilience against toxic assaults.

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