



International Journal of Artificial Intelligence and Machine Learning

Publisher's Home Page: <https://www.svedbergopen.com/>



Research Paper

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Synergistic Role of GGBS and Silica Fume in Enhancing the Strength and Sustainability of M40 Grade Concrete

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Abstract

Researchers study new materials to make concrete that lasts longer and protects nature because people want eco-friendly sustainable permanent concrete. The research project tests M40 grade concrete which uses different levels of recommended material replacement 30 to 60 percent to study its mechanical and durability properties. The experimental program assessed compressive strength and split tensile strength and flexural strength at 28-day and 56-day curing periods. The researchers evaluated durability by testing material samples with three different types of acid and salt and sulfate attacks which were based on their residual compressive strength. The results demonstrate that partial replacement leads to significant enhancements in both long-term strength and durability characteristics of the material. The 40% replacement mix achieved the highest 56-day values with its 54.07 MPa compressive strength and 5.66 MPa split tensile strength and 8.29 MPa flexural strength while the 50% replacement mix maintained strength after acid and sulfate attacks. The testing showed that all combinations experienced a slight decrease in strength after chloride exposure. The study confirms that the produced concrete is suitable for harsh and sustainable environmental applications by identifying the 40-50% replacement range as ideal, which provides balanced enhancements of mechanical performance and durability.

Keywords: Ground Granulated Blast Furnace Slag (GGBS), Silica Fume, M40 Concrete, Mechanical Properties, Sustainable

Introduction

Modern construction practices now prioritize sustainability and durability as their primary requirements because of the current infrastructure expansion that creates excessive demand for concrete. Conventional concrete production requires Portland cement and natural aggregates as its main materials which require extensive energy usage and resources and lead to major carbon dioxide emissions during their extraction and processing. Researchers need to create sustainable cementitious materials which will achieve structural durability throughout their service life while enabling eco-friendly construction through their environmental performance.

The research shows that sustainable concrete through this study requires researchers to identify the best material substitution method which will enhance both mechanical properties and material longevity. The excessive use of replacement materials will damage early performance while the use of too little replacement materials will cause strength loss together with reduced material durability. The research aims to identify the optimal combination which will determine the replacement percentage between strength development and environmental protection. The development of long-term strength requires understanding because it affects later-age performance which determines both service life and structural reliability improvements.

Concrete structures maintain their essential utility value throughout their entire operational period because their concrete materials sustain their strength under both typical use and extreme climate situations which include exposure to acidic and sulfate-bearing and chloride-rich environments. Chemical attack on concrete leads to severe damage because it increases porosity and weakens cementitious materials and accelerates corrosion of metal reinforcements. The study about durability shows that microstructural densification together with lower permeability should be used to improve chemical barrier defense because this method will lower maintenance needs while extending equipment service life, which supports sustainability targets. The research investigates M40 grade concrete's potential as an eco-friendly construction material through its

examination of material properties at different replacement percentages. The research combines a complete durability assessment which tests materials in acid and chloride and sulfate environments with mechanical tests which measure compressive strength and split tensile strength and flexural strength. The research establishes relationships between strength growth and durability performance to determine the replacement range which delivers maximum benefits to durability and structural performance and environmental protection. The research results provide practical guidelines for developing concrete mixtures which maintain sustainability and durability throughout extended periods of structural usage in severe environmental conditions.

Methodology

The researchers conducted systematic experiments to examine how different materials could replace M40 grade concrete and their impact on the concrete's mechanical properties and durability according to sustainable development standards. The approach was developed to guarantee uniformity in data interpretation, testing protocols, and mix preparation.

Materials

The primary binder for the project used Ordinary Portland Cement which meets Indian Standards requirements. The selection of natural fine aggregates and crushed coarse aggregates happened through the process of standard grading evaluation. The team used replacement material at weight percentages of 30% 40% 50% and 60% to create experimental materials while they used a standard M40 mix without any replacement as the control mix. The experimental program used drinking water which meets standards for concrete mixing and curing purposes.



Figure 1: Materials

MIX PROPORTIONING

The M40 grade concrete mix design was completed in compliance with IS 10262 guidelines. Modified mixes were created by partially substituting the conventional constituent at the chosen percentages while keeping the water-binder ratio constant. The control mix was created to reach the desired mean strength. To guarantee comparability of outcomes, all mixes were produced in the same way.

	Cement	GGBS	Silica Fume
MIX-0	100%	-	-
MIX-1	65%	30%	5%
MIX-2	55%	40%	5%
MIX-3	45%	50%	5%
MIX-4	35%	60%	5%

Figure 2: Mix Proportioning**SPECIMEN PREPARATION AND CURING**

Standard specimens were cast for each combination in order to assess its durability and mechanical qualities. Prism specimens were used to assess flexural strength, cylindrical specimens for split tensile strength, and cube specimens for compressive strength testing. Following casting, the specimens were demolded after a day and allowed to cure in water at room temperature until they reached the testing ages of 28 and 56 days.

**Figure 3: Specimen Preparation and Curing****MECHANICAL PROPERTY TESTING**

The testing of cube specimens according to IS 516 standard requirements was performed at 28 days and 56 days to measure their compressive strength while the cylindrical specimens were tested for split tensile strength according to IS 5816 standard requirements and the prism specimens were tested for flexural strength through third-point loading tests according to standard testing procedures. The average results from all tested samples were reported for each blend.



Figure 4: Mechanical Property Testing

DURABILITY TESTING

The experiments tested the durability of the cube specimens through their exposed chemical assault tests. The specimens underwent 28 days of water curing before they were tested in acidic (5% H_2SO_4) and chloride (3.5% NaCl) and sulphate (5. Na_2SO_4) solutions for specific time intervals. The testing process evaluated how chemical substances affected the specimens because the researchers measured their remaining compressive strength after 56 days to determine strength loss percentage.



Figure 5: Durability Testing

DATA ANALYSIS

The researchers checked test results to study how different replacement amounts impacted strength development and durability performance. The researchers needed to compare the control mix with modified mixes to find the best replacement levels which would help them assess performance differences while identifying existing trends. The researchers assessed the results to determine their sustainable advantages

and durability improvements which would enable their future application in structural projects.

Results And Discussion

COMPRESSIVE STRENGTH

The testing results in Figure 6 compare the compressive strength of modified concrete mixes with control concrete mixes at 28 and 56 days. The 30% replacement mix achieved the highest compressive strength at 28 days with a value of 46.66 MPa, which exceeded the control mix by almost 10.5%. The matrix densification process which occurs during early age and the material's enhanced particle packing capabilities, lead to strength improvement. The results showed a gradual reduction in strength for 28-day periods after 30% replacement, which demonstrated that higher replacement levels caused dilution effects.

Table 1. Compressive Strength of Concrete Mixes

Mix ID	28 Days (MPa)	56 Days (MPa)
M40 (Control)	42.22	46.51
30%	46.66	49.03
40%	41.77	54.07
50%	40.14	53.33
60%	37.03	51.25

At 56 days, a distinct trend became apparent which showed that the 40% replacement mix achieved maximum compressive strength at 54.07 MPa while the 50% mix followed with a strength of 53.33 MPa. The ongoing development of strength at advanced ages demonstrates that delayed pozzolanic processes continue to operate which produce secondary calcium silicate hydrate (C-S-H) and refine pore structure. The 60% replacement mix demonstrated proper structural performance when tested against the control mix despite its lower strength compared to other mixes.

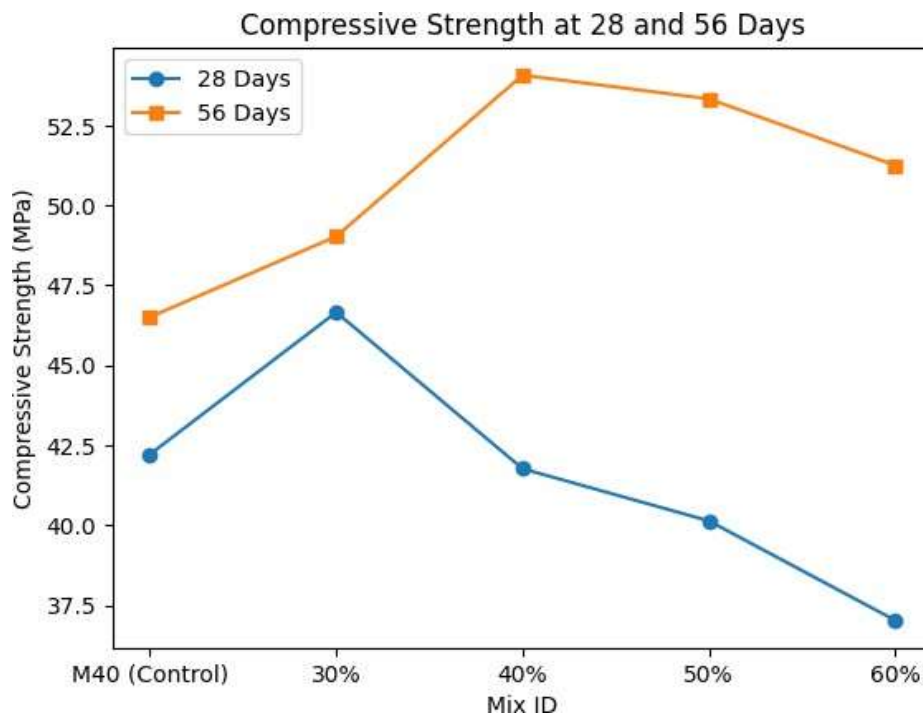


Figure 6. Compressive strength development of concrete mixes at 28 and 56 days.

SPLIT TENSILE STRENGTH

Figure 7 presents the results for split tensile strength. While the changed mixes showed better tensile performance, especially at higher curing ages, the control mix registered a 56-day tensile strength of 4.82 MPa. In comparison to the control mix, the 40% replacement mix produced the greatest 56-day split tensile strength of 5.66 MPa, or almost 17.4% more.

Table 2. Split Tensile Strength of Concrete Mixes

Mix ID	28 Days (MPa)	56 Days (MPa)
M40	4.56	4.82
30%	4.95	5.09
40%	4.15	5.66
50%	3.91	5.18
60%	3.44	4.01

Better stress transfer between the paste and aggregates and enhanced interfacial transition zone (ITZ) quality are responsible for this improvement. Tensile strength decreased at replacement levels higher than 50%, most likely as a result of increasing porosity and insufficient binding phases.

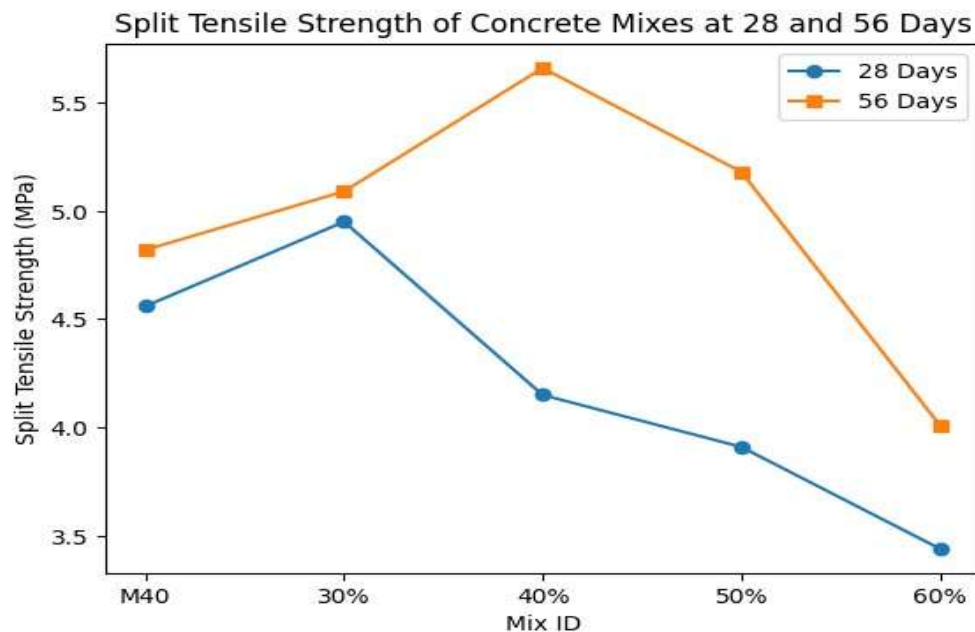


Figure 7. Variation of split tensile strength with replacement percentage.

FLEXURAL STRENGTH

Figure 8 shows how the flexural strength of different concrete mixes has developed over time. The modified mixes demonstrated higher flexural strength than the control mix according to testing results. At 56 days, the 40% replacement mix achieved its maximum flexural strength of 8.29 MPa because it exhibited enhanced load distribution and improved crack-bridging performance.

Table 3. Flexural Strength of Concrete Mixes

Mix ID	28 Days (MPa)	56 Days (MPa)
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M40	5.22	5.68
30%	7.10	7.39
40%	7.75	8.29
50%	7.02	7.61
60%	6.33	6.53

The flexural strength of materials improves because their microstructure becomes denser and their bonding strength increases. The flexural strength of the material decreased after 40 to 50 percent replacement but remained above the level of the control mix.

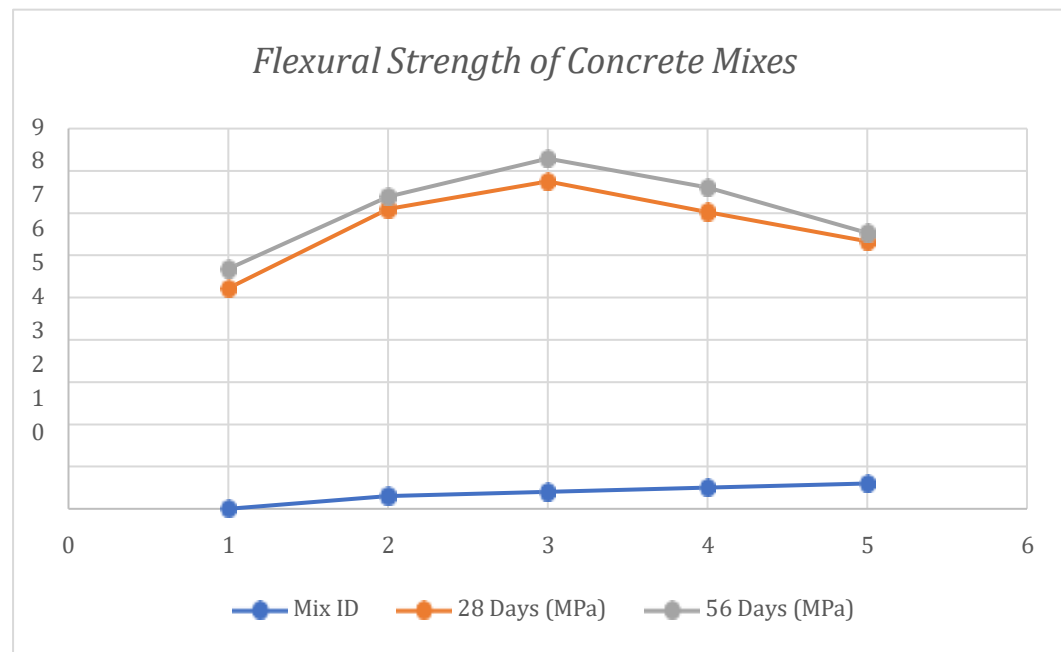


Figure 8. Flexural strength variation of concrete mixes at different curing ages.

DURABILITY PERFORMANCE ACID ATTACK RESISTANCE

The diagram in Figure 9 displays the resistance level of various concrete mixtures toward acid exposure. The control mix demonstrated a strength reduction of 15.32% following 56 days of exposure. The changed mixes, on the other hand, exhibited much less degradation; the 50% replacement mix had the lowest strength loss of 4.81%

Table 4. Acid Attack Resistance (5% H₂SO₄)

Mix ID	28 Days (MPa)	56 Days (MPa)	Strength Loss (%)
M40	42.22	26.91	15.32
30%	42.66	30.44	12.22

40%	41.77	32.88	8.89
50%	40.14	35.33	4.81
60%	37.03	31.71	5.32

The improved resistance to acids occurs because calcium hydroxide concentration drops and the upgraded pore structure controls acid penetration while stopping chemical degradation of hydration products.

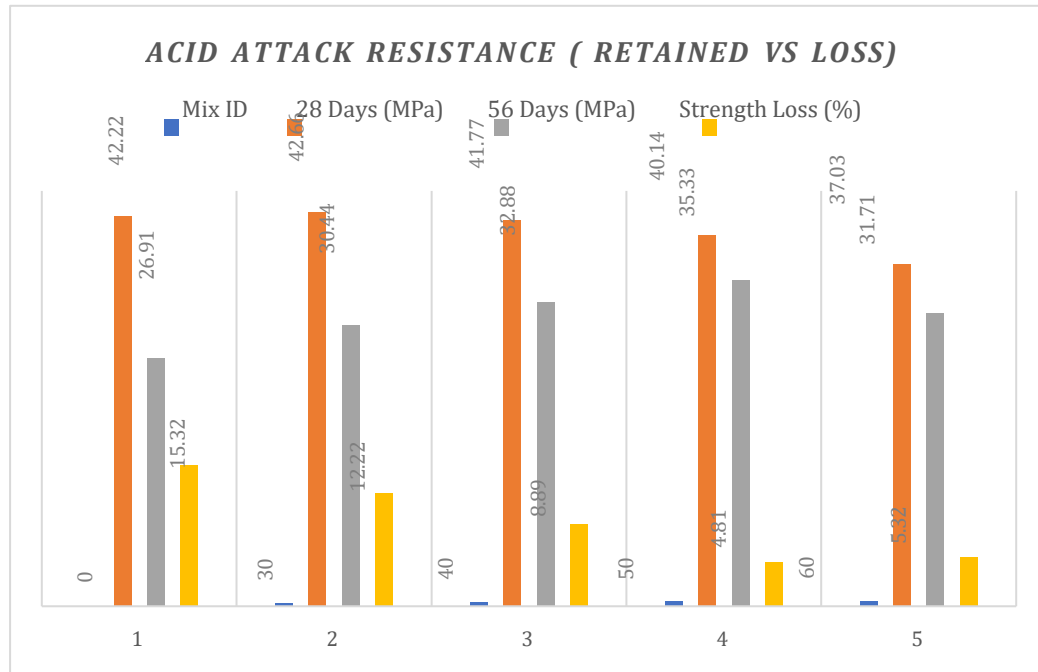


Figure 9. Percentage strength loss under acid attack conditions.

CHLORIDE ATTACK RESISTANCE

Figure 10 displays the strength reduction results of concrete mixtures which underwent chloride exposure testing. All tested combinations exhibited minimal strength reductions which demonstrated their strong resistance against chloride penetration. The 50% replacement mix demonstrated the lowest strength loss at 1.12% which showed better durability performance in marine environments and chloride-rich conditions.

Table 5. Chloride Attack Resistance (3.5% NaCl)

Mix ID	28 Days (MPa)	56 Days (MPa)	Strength Loss (%)
M40	42.22	40.42	1.80
30%	42.66	41.03	1.63
40%	41.77	40.56	1.21
50%	40.14	39.02	1.12
60%	37.03	35.75	1.28

The introduction of the new treatment greatly affected the reduction of chloride atoms migrating to the denser micromatrix of the concrete portion as a result of chloride ions during the ultimate ionizing up to

seasons of suffering.

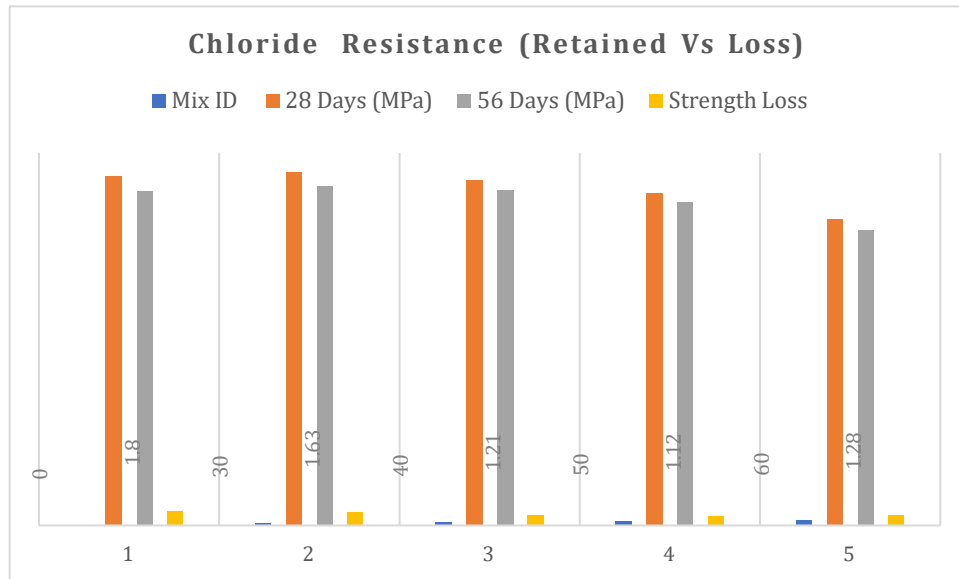


Figure 10. Chloride attack resistance of concrete mixes.

3.4.3 Sulphate Attack Resistance

Figure 11 displays the results of the sulphate attack examination. The control mix showed severe deterioration with a strength loss of 15.89% whereas the 50% replacement mix demonstrated excellent resistance with only 2.28% strength loss.

Table 6. Sulphate Attack Resistance (5% Na₂SO₄)

Mix ID	28 Days (MPa)	56 Days (MPa)	Strength Loss (%)
M40	42.22	24.33	15.89
30%	42.66	27.35	15.31
40%	41.77	31.25	10.52
50%	40.14	37.86	2.28
60%	37.03	30.58	6.45

This advance is succinctly described by the greater stability of the cementitious binder with respect to aggressive media, while at the same time, the cementitious binder's relative lack of good efficiency with respect to the cement constituents gradually reduces the sulfate attack.

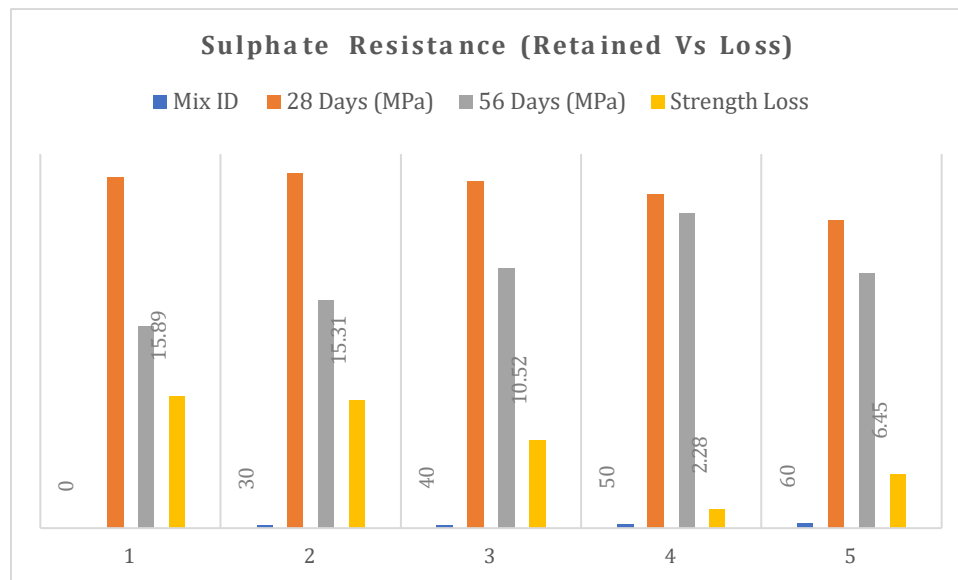


Figure 11. Strength loss of concrete mixes under sulphate attack.

4. Conclusion

The experimental study shows that partial replacement of M40 grade concrete produces significant changes which affect both its mechanical strength and durability properties. The study found that 40% replacement level produces maximum compressive strength and split tensile strength and flexural strength at 56 days. The research demonstrates that cementitious matrix microstructural densification together with effective bond strength development results in superior strength development throughout time. The standard concrete testing shows that concrete exhibits better acid and chloride and sulphate resistance against standard concrete testing methods. The 50% replacement mix showed the least amount of strength loss after acid and sulphate exposure, indicating its greater performance in challenging environmental circumstances, even though both combinations showed very little degradation under chloride assault. The ideal replacement range for strength and durability properties assessment lies between 40 and 50 percent based on total strength and durability property analysis. The results demonstrate that the proposed concrete mix serves as a sustainable and technically effective structural solution for applications which require superior long-term performance and durability under chemically harsh conditions.

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