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Research Paper

DURABILITY ASSESSMENT OF BASALT FIBER REINFORCED RECYCLED AGGREGATE CONCRETE EXPOSED TO AGGRESSIVE CHEMICAL ENVIRONMENTS

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Abstract:

The utilization of recycled aggregates in concrete contributes significantly to sustainability; however, durability concerns under aggressive environmental conditions limit their widespread application. This study investigates the durability performance of basalt fiber reinforced recycled aggregate concrete (BFRC) exposed to acidic, sulphate, and chloride environments, focusing exclusively on long-term durability indicators. Concrete mixes were prepared with varying recycled aggregate contents and basalt fiber dosages of 0%, 0.2%, 0.4%, and 0.6%. Durability evaluation was carried out through acid attack using sulphuric acid, sulphate attack using magnesium sulphate solution, and rapid chloride penetration test (RCPT) in accordance with relevant standards for M20 grade concrete. Residual compressive strength was assessed after 28, 56, and 90 days of chemical exposure, while chloride permeability was evaluated at 90 days. The results indicate that recycled aggregate concrete without fiber reinforcement exhibits increased vulnerability to aggressive environments, particularly under acidic exposure. The inclusion of basalt fibers significantly enhances durability performance by improving residual strength retention and reducing chloride ion penetration. Among the fiber dosages investigated, 0.4% basalt fiber consistently demonstrated superior performance across all durability tests, exhibiting the lowest strength degradation under acid and sulphate attack and achieving low chloride permeability classification. The findings highlight the potential of basalt fiber reinforcement to offset durability limitations associated with recycled aggregates, enabling the production of sustainable concrete with enhanced service life and reduced maintenance requirements in aggressive environments.

Key words: Basalt fiber reinforced concrete; Recycled aggregate concrete; Durability performance; Acid attack; Sulphate attack; Rapid chloride penetration test; Sustainable concrete; Aggressive environments

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1. Introduction

Concrete durability has become a primary design requirement as infrastructure is increasingly exposed to aggressive environments such as industrial effluents, acidified soils, marine chlorides, and sulphate-rich groundwater. Premature deterioration is not only a technical issue (loss of strength, cracking, spalling, reinforcement corrosion), but also a sustainability issue because repair and replacement increase embodied energy, cost, and CO_2 emissions across the service life. Modern durability thinking therefore emphasizes "build once, last longer" as a direct pathway to sustainability, alongside the use of alternative materials that reduce depletion of natural resources and landfill burden [1], [2]. From a sustainability perspective, the concrete sector faces two linked challenges. First, Portland cement production is energy intensive and a major source of CO_2 emissions; hence durability improvements that extend service life can reduce life-cycle impacts even when the initial mix design remains conventional [1], [2]. Second, the extraction of natural aggregates and disposal of construction and demolition waste create substantial environmental pressure. Recycled concrete aggregate (RCA) has been widely studied as a strategy to address this issue, and many investigations conclude that RCA can be used in structural and non-structural concrete with suitable processing and mix design [3]– [7]. However, RCA concrete may be more sensitive to transport-driven deterioration mechanisms because attached old mortar and microcracks can increase permeability and facilitate ingress of aggressive ions in some cases [5], [6]. This has encouraged research on complementary approaches that refine pore structure and crack control, including mineral admixtures and fiber reinforcement, to achieve both sustainability and durability objectives [6]–[8]. Among the durability threats, chemical attack by acids and sulphates, and chloride ingress leading to corrosion, are particularly critical for reinforced concrete in urban/industrial regions and coastal zones. Acid attack, especially by sulfuric acid, is severe because it dissolves calcium-bearing hydration products and can form expansive/soft reaction products that reduce cohesion and cause surface scaling, mass loss, and rapid strength reduction. Experimental studies have shown that sulfuric acid attack can be assessed through indicators such as weight loss, dimensional changes, and residual strength, and that deterioration rate is strongly influenced by acid concentration, exposure regime, and concrete quality (w/c ratio, binder composition, and permeability) [9], [10]. In practice, acid exposure is often coupled with abrasion or wet–dry cycling, which accelerates damage by repeatedly renewing the aggressive medium at the concrete surface and by enabling deeper penetration through microcracks [10]. Sulphate attack is another common durability problem in foundations, sewage networks, marine soils, and industrial environments. Sulphate ions can react with cement hydration products to form expansive phases and can also cause physical damage through crystallization pressures, depending on the sulphate cation (e.g., sodium vs. magnesium), temperature, and moisture conditions. The mechanism and progression of sulphate attack have been extensively discussed in classical studies, which highlight that magnesium sulphate can be particularly damaging because it can decalcify C–S–H and weaken the binding matrix [11], [12]. Since field sulphate exposure is often variable (immersion, partial immersion, wet–dry cycles), laboratory methods must be selected carefully to represent the intended service condition. Standardized testing approaches such as ASTM C1012 provide a structured basis to assess sulphate resistance trends in cementitious systems, while acknowledging that real structures may experience combined actions and longer exposure times [13]. Chloride ingress is closely associated with corrosion of steel reinforcement, which remains one of the costliest durability problems globally. Concrete permeability is therefore a key performance target, and rapid test methods are frequently used for quality control and comparative evaluation of mixtures. The Rapid Chloride Permeability Test (RCPT), standardized as ASTM C1202, measures electrical charge passed through a saturated specimen under an applied potential and provides a rapid indication of resistance to ionic penetration in many practical cases [14]. Although RCPT does not directly measure diffusion and can be affected by pore solution conductivity and temperature rise, it remains widely used to compare mixtures and to support durability-based specifications when interpreted with proper care and supplementary indicators (e.g., resistivity, absorption, diffusion tests) [14], [15]. In this context, fiber reinforcement is increasingly considered not only for mechanical benefits, but also for durability enhancement through crack control. Fibers can bridge microcracks, limit crack width, and reduce connectivity of transport pathways, which may slow ingress of acids, sulphates, and chlorides. The durability benefit is not automatic: it depends on fiber type, dosage, dispersion, matrix quality, and the fiber–matrix interfacial transition zone (ITZ). Basalt fiber, produced from melted basalt rock, has gained attention as an inorganic fiber with high tensile strength, good thermal stability, and corrosion resistance compared with some conventional fibers. Importantly, basalt fibers are often positioned as a more sustainable reinforcement option due to natural raw material sourcing and potential for durability-driven service-life extension [16]–[18]. Studies on basalt fiber reinforced concrete (BFRC) under sulphate environments report that fiber addition can slow pore development and reduce deterioration rate, while excessive fiber content may negatively affect workability and create voids that offset durability gains [16], [19]. Investigations on self-compacting concrete with chopped basalt fibers have also shown that basalt fiber can improve strength-related properties while affecting permeability indices, including RCPT and water penetration depth, indicating that optimization is necessary rather than simply maximizing fiber content [17]. For chloride-related durability, work examining the combined effect of basalt fibers and mineral admixtures has reported improved resistance to chloride penetration due to refined pore structure and reduced cracking, again emphasizing that the overall system (binder

+ fiber + curing) governs transport performance [18]. When the sustainability objective is broadened to include aggregate conservation and waste utilization, BFRC becomes relevant in two ways. First, basalt fiber can be used in conventional natural-aggregate concrete to extend service life in aggressive exposure, thereby reducing life-cycle emissions and maintenance demand [1], [2]. Second, in mixes incorporating RCA, fiber reinforcement may help compensate for RCA-related permeability and microcracking concerns by limiting crack propagation and improving residual performance under durability attacks [6]–[8], [20]. A key point from RCA literature is that durability performance is highly dependent on mixture design and exposure type; for instance, long-term sulphate exposure studies on recycled aggregate concrete indicate that sulphate ingress and reaction products evolve over extended periods, and the role of attached mortar can become significant in aggressive sulphate solutions [21]. This supports the need to study durability through targeted tests (acid, sulphate, chloride transport) rather than relying only on short-term strength indices.

Despite growing interest, practical design and publication trends show that durability-focused studies on BFRC are still less consolidated than strength-focused studies, and results sometimes appear inconsistent across test methods and exposure regimes. Two reasons are common: (i) durability is controlled by transport and cracking, which are sensitive to curing, compaction, and pore structure; and (ii) fiber addition can simultaneously reduce crack widths while introducing dispersion-related voids if workability is not managed. Therefore, durability assessment of BFRC must explicitly track performance under representative chemical exposures (acid and sulphate immersion) and ionic transport tests (RCPT), and must present outcomes in terms of residual properties and sustainability implications (service-life extension and reduced repair demand). In this study, M20-grade basalt fiber reinforced concrete is evaluated using acid attack, sulphate attack, and RCPT as the core durability indicators, with the sustainability emphasis placed on durability-driven life extension and material efficiency.

2. Literature Review

Durability of concrete incorporating recycled aggregates has been extensively investigated due to increasing environmental concerns related to natural aggregate depletion and construction and demolition waste management. Numerous studies have reported that recycled aggregate concrete (RAC) generally exhibits higher water absorption, increased porosity, and inferior resistance to aggressive environments when compared with conventional concrete [3]–[7]. These drawbacks are primarily attributed to the presence of adhered old mortar, pre-existing microcracks, and a weaker interfacial transition zone, which collectively increase permeability and facilitate ingress of aggressive agents [5], [6]. Consequently, transport-controlled deterioration mechanisms become more pronounced in RAC, particularly under chemical exposure and chloride-rich environments.

Resistance of recycled aggregate concrete to acid attack has been identified as a major durability concern. Sulphuric acid exposure is considered especially aggressive because it dissolves calcium-rich hydration products and can generate soft or expansive reaction layers that progressively weaken the cement matrix. Attiogbe and Rizkalla [9] demonstrated that sulphuric acid attack leads to significant strength loss and surface degradation, with deterioration rate strongly dependent on concrete permeability and exposure duration. Subsequent investigations confirmed that RAC experiences more rapid degradation under acidic conditions compared to natural aggregate concrete, owing to easier acid penetration through connected pores and microcracks [10], [21]. Long-term immersion studies further emphasize that residual compressive strength is a reliable indicator of acid-induced deterioration, as it reflects both surface damage and internal matrix weakening [10]. Sulphate attack is another critical durability issue, particularly in foundations, sewage structures, and regions with sulphate-bearing soils and groundwater. The mechanism of sulphate attack depends on the sulphate type and exposure conditions. Santhanam et al. [11], [12] highlighted that magnesium sulphate attack is more detrimental than sodium sulphate attack because it involves decalcification of calcium silicate hydrate in addition to expansive reactions, leading to progressive loss of binding capacity. Research on RAC exposed to sulphate environments indicates that recycled aggregates can intensify sulphate-induced degradation due to higher permeability and greater ion accessibility [19], [21]. Bassuoni and Nehdi [19] further reported that sulphate damage is significantly accelerated under combined actions such as wetting–drying cycles and sustained loading, which are common in real service conditions. Chloride ingress is closely associated with corrosion of steel reinforcement and is therefore one of the most critical durability concerns in reinforced concrete structures. Transport of chloride ions is governed by pore structure, crack connectivity, and moisture state of concrete. The Rapid Chloride Permeability Test (RCPT) is widely used as a comparative durability indicator to assess resistance to ionic penetration [14]. Although RCPT does not directly measure chloride diffusion and is influenced by pore solution conductivity, it remains useful for comparative evaluation of mixtures when interpreted with caution [15]. Studies on RAC consistently report higher RCPT values compared to conventional concrete, confirming increased susceptibility to chloride ingress due to higher porosity and connected pore networks [5], [7]. To overcome durability limitations of recycled aggregate concrete, several enhancement strategies have been proposed, including the use of supplementary cementitious materials and fiber reinforcement. Fiber addition has attracted increasing interest because it improves crack control without significantly altering mix proportions. Discrete fibers restrict microcrack initiation and propagation, thereby reducing crack width and limiting transport pathways for aggressive ions. Among available fibers, basalt fiber has emerged as a promising reinforcement due to its non-corrosive nature, high tensile strength, and good compatibility with cementitious matrices

[16]–[18]. Basalt fibers are derived from natural basalt rock and do not require complex chemical processing, which supports their use in environmentally conscious concrete applications. Experimental studies on basalt fiber reinforced concrete (BFRC) indicate that fiber addition can improve durability-related performance when used at optimized dosages. Meng et al. [16] reported enhanced resistance to magnesium sulphate attack in BFRC, attributed to improved crack control and delayed sulphate ingress. Similarly, Guo et al. [18] observed reduced chloride penetration in BFRC mixes, emphasizing that fiber dosage and dispersion play a critical role in achieving durability benefits. Algin and Ozen [17] noted that excessive basalt fiber content can negatively affect workability and introduce entrapped air, potentially increasing permeability and offsetting durability gains. These findings highlight the importance of identifying an optimum fiber content rather than assuming continuous improvement with increasing fiber dosage. The combined use of recycled aggregates and basalt fiber reinforcement has been explored to a limited extent. Available studies suggest that fiber reinforcement can partially compensate for the inherent durability weaknesses of RAC by limiting microcrack development and reducing crack connectivity [6]–[8]. However, most existing investigations focus either on mechanical performance or on a single durability mechanism, such as chloride penetration or sulphate resistance, without providing a comprehensive evaluation across multiple aggressive environments. Furthermore, durability-oriented studies on normal-strength concrete, such as M20 grade, incorporating both recycled aggregates and basalt fibers remain scarce, despite the widespread use of this grade in practical construction.

Based on the reviewed literature, it is evident that a systematic durability-focused investigation addressing acid attack, sulphate attack, and chloride penetration within a consistent experimental framework is required to assess the practical feasibility of basalt fiber reinforced recycled aggregate concrete. This identified research gap forms the basis of the present study, which emphasizes durability performance and sustainability through service-life enhancement rather than strength maximization.

3. Materials and Experimental Program

This section describes the materials used, mix proportions, specimen preparation, curing procedure, and durability testing program adopted to evaluate the performance of basalt fiber reinforced recycled aggregate concrete. The experimental program was designed to focus exclusively on durability behaviour under aggressive environments, namely acid attack, sulphate attack, and chloride penetration.

3.1 Cement

Ordinary Portland Cement (OPC) 53 grade conforming to relevant Indian Standards was used as the binding material in all concrete mixes. The cement was fresh, free from lumps, and stored under dry conditions to prevent moisture ingress. The cement content was selected to achieve M20 grade concrete, which represents a commonly used strength class in general construction and infrastructure applications.

3.2 Fine aggregate

Natural river sand was used as the fine aggregate in all mixes. The sand was clean, well-graded, and free from clay lumps, silt, organic matter, and other deleterious impurities. Prior to mixing, the sand was brought to a consistent moisture condition (preferably saturated surface-dry) to avoid unintended variation in effective water content among mixes. The grading and basic quality requirements were maintained in line with standard specifications for concrete fine aggregates.

3.3 Coarse Aggregate and Recycled Aggregate

Natural coarse aggregate and recycled concrete aggregate (RCA) were used as the coarse aggregate constituents. The recycled aggregate was obtained from crushed waste concrete sourced from demolished structural elements. After crushing, the recycled aggregate was sieved to the required size range and thoroughly washed to remove loose mortar particles and dust. The RCA was air-dried before use. Partial replacement of natural coarse aggregate with recycled aggregate was adopted to assess durability performance under sustainable material utilization.

3.4 Basalt fiber

Chopped basalt fibers were used as discrete reinforcement in the concrete mixes. A constant fiber length of 30 mm was adopted throughout the experimental program. Basalt fibers were selected due to their non-corrosive nature and their ability to bridge microcracks, which can reduce crack connectivity and limit the ingress of aggressive agents. Fibers were added at dosages of 0%, 0.2%, 0.4%, and 0.6% (by weight of cement). To minimize fiber balling and ensure uniform distribution, fibers were introduced gradually during mixing and mixing time was slightly increased until visible uniformity was achieved.

3.5 Mix Proportions and Mix Identification

Concrete mixes were designed for M20 grade strength with varying recycled aggregate replacement levels and basalt fiber dosages. A control mix without fibers and recycled aggregate was prepared for comparison. Mix identification was carried out systematically to represent the combined effect of recycled aggregate content and basalt fiber dosage. All mixes were prepared using the same water–cement ratio to ensure consistency and to isolate the effect of material modifications on durability performance.

3.6 Specimen Preparation and Curing

Concrete was mixed using a mechanical mixer. Dry materials were first blended to achieve uniformity, followed by gradual addition of water. Basalt fibers were introduced slowly during mixing to ensure proper dispersion. Fresh concrete was cast into standard cube moulds and compacted using a vibrating table. After casting, specimens were covered to prevent moisture loss and demoulded after 24 hours. All specimens were cured in clean water at ambient laboratory temperature for 28 days prior to durability exposure. After initial curing, specimens were subjected to different aggressive environments depending on the durability test.

3.7 Durability Testing Program

Durability performance was evaluated through acid attack, sulphate attack, and rapid chloride penetration test (RCPT). These tests were selected to represent common aggressive exposure conditions encountered by concrete structures.

3.7.1 Acid attack test

Acid resistance was evaluated by immersion in 5% sulphuric acid (H_2SO_4) solution. After 28 days of water curing, specimens were immersed in the acid solution for exposure durations of 28, 56, and 90 days. The solution was periodically renewed to maintain the intended concentration and aggressiveness. At the end of each exposure period, specimens were removed, rinsed to remove surface deposits, gently surface-dried, and tested for residual compressive strength to quantify the extent of deterioration.

3.7.2 Sulphate attack test

Sulphate resistance was assessed by immersion in 5% magnesium sulphate ($MgSO_4$) solution. Following 28 days of water curing, specimens were immersed in the sulphate solution for 28, 56, and 90 days. The solution was maintained at the intended concentration and refreshed periodically. After the designated exposure period, specimens were removed, surface-cleaned, and tested for residual compressive strength. Performance was evaluated based on strength retention relative to the corresponding control specimens.

3.7.3 Rapid chloride penetration test (RCPT)

Resistance to chloride ion penetration was evaluated using the Rapid Chloride Permeability Test (RCPT) in accordance with ASTM C1202. The test was conducted at 90 days curing age to capture the stabilized transport characteristics of the concrete matrix.

Specimen preparation

1. From the concrete specimens, discs of 50 mm thickness were prepared. If cylinders were used, discs were cut from the mid-height region to avoid end effects. The cut faces were made plane and smooth.
2. The specimens were pre-conditioned to a saturated state before testing. In the standard procedure, vacuum saturation is adopted to ensure consistent moisture condition and electrical continuity through the specimen. Typically, the discs are placed under vacuum for a specified period, followed by soaking in de-aired water to achieve saturation.

Test setup

3. The RCPT cell consists of two compartments separated by the concrete disc, sealed using gaskets to prevent leakage.
4. One compartment is filled with sodium chloride (NaCl) solution (commonly 3.0% by mass), and the other compartment is filled with sodium hydroxide (NaOH) solution (commonly 0.3 N). This creates an ionic environment and drives ion movement under an applied electrical potential.
5. A direct current (DC) potential difference of 60 V is applied across the specimen, with electrical terminals connected to the solutions in the two compartments.

6. Once voltage is applied, the current passing through the specimen is recorded at regular intervals of every 30 minutes over a total test duration of 6 hours.
7. During the test, temperature rise in the cell can influence current readings. Therefore, the test is performed under controlled laboratory conditions, and temperature is monitored to ensure repeatability.
8. The total charge passed (Q), expressed in coulombs, is calculated from the measured current readings using numerical integration over the 6-hour period. In practice, the standard method sums the current values recorded at each time interval using the ASTM-recommended calculation approach to obtain total coulombs.

4. Results and Discussion

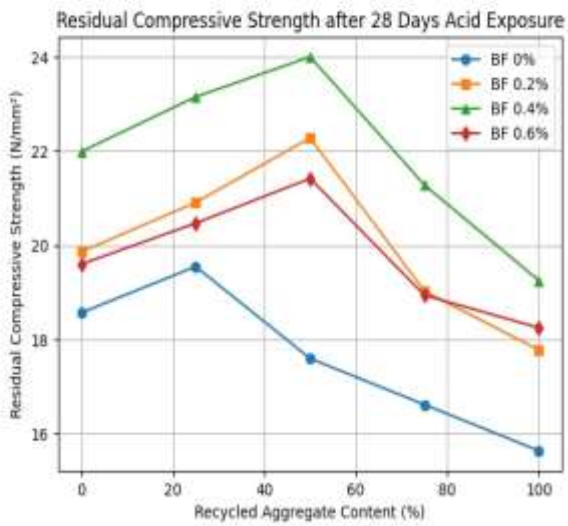
4.1 Acid attack test result

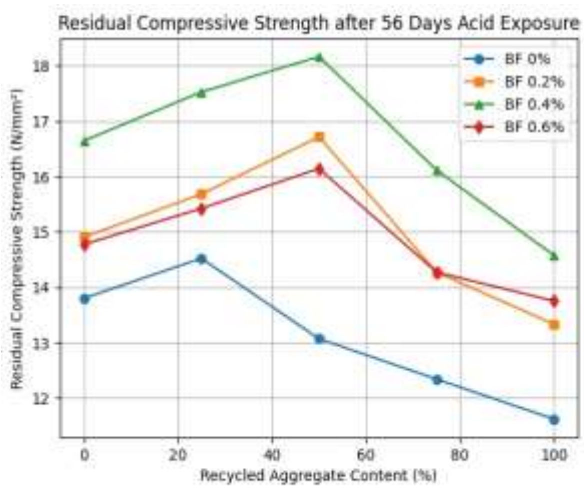
Acid attack is considered one of the most severe durability challenges for cement-based materials, particularly in industrial zones, sewage environments, and areas exposed to acidic effluents. Sulphuric acid is especially aggressive because it reacts with calcium-rich hydration products, leading to decalcification of the cement matrix, surface softening, and progressive loss of strength. In recycled aggregate concrete, susceptibility to acid attack is often higher due to increased porosity and the presence of attached old mortar, which can accelerate acid ingress. Therefore, evaluating residual compressive strength after acid exposure provides a direct and reliable measure of degradation severity and durability performance. In this study, the acid resistance of basalt fiber reinforced recycled aggregate concrete was assessed by immersing specimens in 5% sulphuric acid (H_2SO_4) solution. Residual compressive strength was measured after 28, 56, and 90 days of exposure to examine both short-term and prolonged degradation behaviour. The influence of recycled aggregate replacement level and basalt fiber dosage on strength retention was analysed to identify durability trends and optimum fiber content.

4.2 Effect of Acid Attack on Residual Compressive Strength

The residual compressive strength results after acid exposure are drafted in graphs in Figure 4 (a-c). For all mixes, a continuous reduction in compressive strength was observed with increasing immersion duration from 28 to 90 days, confirming the progressive nature of sulphuric acid-induced deterioration. This reduction is attributed to dissolution of cement hydration products and weakening of the binder matrix due to sustained acid penetration.

For mixes without basalt fiber (BF = 0%), a clear decline in residual strength was observed with increasing recycled aggregate content at all exposure ages. At 28 days of acid immersion, the control mix with natural aggregates exhibited higher residual strength compared to mixes containing recycled aggregates. As recycled aggregate replacement increased from 25% to 100%, residual strength decreased gradually, indicating higher vulnerability of recycled aggregate concrete to acid attack. This trend became more pronounced at 56 and 90 days of exposure, reflecting the cumulative effect of acid ingress through the more permeable microstructure associated with recycled aggregates. The incorporation of basalt fibers significantly improved acid resistance across all recycled aggregate levels. At a fiber dosage of 0.2%, noticeable improvement in residual compressive strength was observed at all immersion ages compared to corresponding non-fiber mixes.





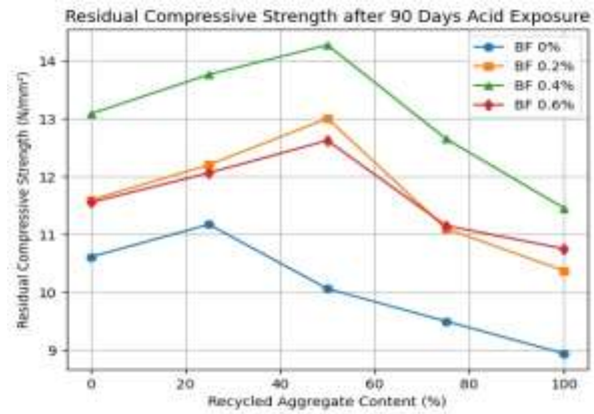


Figure 4(a–c). Residual compressive strength of basalt fiber reinforced recycled aggregate concrete after 28, 56, and 90 days of sulphuric acid exposure.

The improvement was more evident at longer exposure durations, suggesting that basalt fibers contributed to delaying crack propagation and restricting acid penetration during prolonged exposure. Among the investigated fiber dosages, mixes containing 0.4% basalt fiber consistently exhibited the highest residual compressive strength at 28, 56, and 90 days of acid immersion. At 90 days, these mixes showed superior strength retention even at higher recycled aggregate contents, demonstrating the effectiveness of basalt fiber in mitigating acid-induced degradation.

Among the investigated fiber dosages, mixes containing 0.4% basalt fiber consistently exhibited the highest residual compressive strength at 28, 56, and 90 days of acid immersion. At 90 days, these mixes showed superior strength retention even at higher recycled aggregate contents, demonstrating the effectiveness of basalt fiber in mitigating acid-induced degradation. The enhanced performance at 0.4% fiber dosage is attributed to effective crack-bridging action, which limits microcrack widening and reduces connectivity of pathways available for acid ingress. Further increase in fiber dosage to 0.6% did not result in additional improvement in acid resistance. Although 0.6% fiber mixes performed better than non-fiber mixes, their residual strength values were generally lower than those of 0.4% fiber mixes. This behaviour suggests that excessive fiber content may lead to reduced workability and possible fiber clustering, which can introduce localized voids and reduce matrix compactness, thereby offsetting the benefits of crack control. Overall, the acid attack results clearly demonstrate that basalt fiber reinforcement improves the durability of recycled aggregate concrete under aggressive acidic conditions. The optimum performance was achieved at a basalt fiber dosage of 0.4%, beyond which the durability benefit diminished. These findings indicate that appropriate fiber optimization is essential for achieving improved acid resistance rather than simply increasing fiber content.

The observed acid resistance trends are consistent with earlier studies. Attiogbe and Rizkalla (1988) reported that sulphuric acid attack causes progressive strength loss due to dissolution of cement hydration products, with higher degradation in more permeable concretes such as recycled aggregate concrete. The improvement in residual compressive strength achieved through basalt fiber addition in the present study agrees with the findings of Meng et al. (2018), who attributed enhanced chemical resistance of basalt fiber reinforced concrete to effective crack-bridging and delayed ingress of aggressive ions. Guo et al. (2019) further emphasized that durability improvement is strongly dependent on fiber dosage, which supports the optimum performance observed at 0.4% basalt fiber in this investigation.

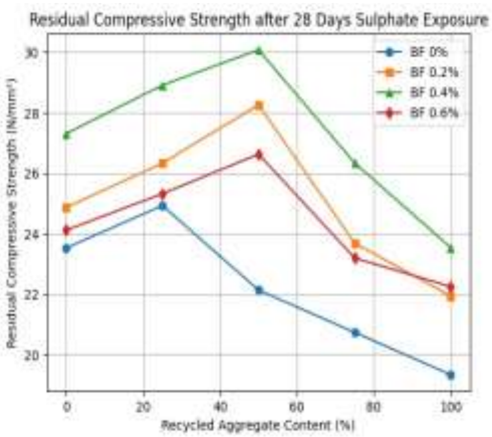
4.2 Sulphate attack test result

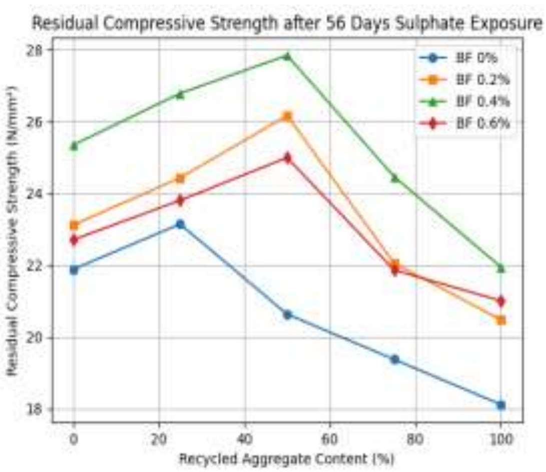
Sulphate attack is a common durability concern for concrete structures exposed to sulphate-bearing soils, groundwater, and industrial environments. Unlike acid attack, sulphate attack generally progresses at a slower rate; however, prolonged exposure can lead to formation of expansive reaction products and decalcification of the cement matrix, resulting in cracking and gradual strength loss. In the present study, sulphate resistance of basalt fiber reinforced recycled aggregate concrete was evaluated by immersion in 5% magnesium sulphate ($MgSO_4$) solution, and residual compressive strength was measured after 28, 56, and 90 days of exposure.

4.2.1 Effect of Sulphate Attack on Residual Compressive Strength

The residual compressive strength results obtained after exposure to 5% magnesium sulphate solution are presented in Table 2 and Figures 6(a–c). For all mixes, a gradual reduction in compressive strength was observed with increasing exposure duration from 28 to 90 days, indicating progressive sulphate-induced deterioration. However, the rate of strength loss under sulphate exposure was noticeably lower than that observed under acid attack, confirming that sulphate attack is comparatively less aggressive for the investigated concrete mixes. For mixes without basalt fiber reinforcement (BF = 0%), residual compressive strength at 28 days of sulphate exposure ranged from 23.53 N/mm² for the control mix to 19.34 N/mm² for 100% recycled aggregate replacement. At 56 days, these values reduced to the range of 21.88–18.11 N/mm², and further decreased to 19.25–15.82 N/mm² at 90 days of exposure. The continuous reduction with increasing recycled aggregate content highlights the increased susceptibility of recycled aggregate concrete to sulphate ingress due to higher porosity and weaker interfacial transition zones. The incorporation of basalt fibers resulted in a clear improvement in residual compressive strength at all recycled aggregate levels and exposure durations. At a fiber dosage of 0.2%, residual strength at 28 days increased to values between 24.87 and 21.94 N/mm², compared to corresponding non-fiber mixes. Similar improvement was observed at 56 and 90 days, indicating that even a low fiber dosage contributes to enhanced sulphate resistance by restricting early microcrack development. The highest sulphate resistance was consistently achieved in mixes containing 0.4% basalt fiber. At 28 days of sulphate exposure, residual compressive strength values for these mixes ranged from 27.31 N/mm² (0% RA) to 23.54 N/mm² (100% RA), with a peak value of 30.08 N/mm² observed at 50% recycled aggregate replacement. After 90 days of exposure, these mixes retained strengths in the range of 23.06–19.88 N/mm², which were significantly higher than those of non-fiber and 0.2% fiber mixes. This demonstrates the effectiveness of 0.4% basalt fiber in limiting sulphate-induced damage over prolonged exposure. Further increase in fiber dosage to 0.6% did not yield additional improvement in sulphate resistance. Although residual compressive strength values at 28 days (approximately 24.12–22.25 N/mm²) were higher than those of non-fiber mixes, they remained lower than the corresponding values for 0.4% fiber mixes. A similar trend was observed at 56 and 90 days. This behaviour suggests that excessive fiber content may adversely affect matrix compactness due to reduced workability or fiber clustering, thereby limiting the overall durability benefit. Overall, the sulphate attack results clearly indicate that basalt fiber reinforcement enhances the durability of recycled aggregate concrete under sulphate exposure. An optimum basalt fiber dosage of **0.4%** provides the best resistance to sulphate-induced deterioration by effectively controlling crack propagation and reducing sulphate ion ingress. The results further confirm that, although sulphate attack causes gradual strength reduction, appropriate fiber optimization can significantly improve long-term durability and service-life performance of recycled aggregate concrete.

The sulphate resistance trends observed in this study are consistent with findings reported in earlier investigations. Santhanam, Cohen, and Olek (2002) explained that magnesium sulphate attack is particularly damaging due to decalcification of calcium silicate hydrate, leading to gradual strength reduction rather than rapid surface deterioration. Similar behaviour has been reported for recycled aggregate concrete, where higher permeability facilitates sulphate ingress and accelerates degradation under prolonged exposure. The improved residual compressive strength achieved with basalt fiber incorporation in the present study agrees with observations by Meng et al. (2018), who reported enhanced sulphate resistance in basalt fiber reinforced concrete due to improved crack control and delayed ion penetration. The optimum performance observed at 0.4% basalt fiber dosage is also in line with earlier findings that emphasize the importance of fiber optimization to achieve effective durability enhancement under sulphate environments.





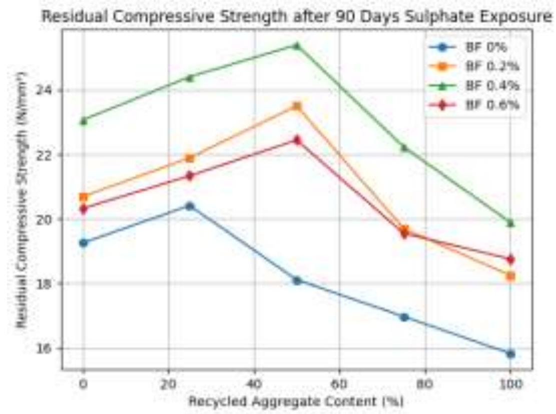


Figure 6(a–c). Residual compressive strength of basalt fiber reinforced recycled aggregate concrete after 28, 56, and 90 days of magnesium sulphate exposure.

4.3 Rapid Chloride Penetration Test (RCPT) Results

Resistance to chloride ion penetration is a critical durability parameter for reinforced concrete structures exposed to marine environments, de-icing salts, and chloride-bearing groundwater. Chloride ingress governs the initiation of steel reinforcement corrosion and is strongly influenced by pore connectivity, microcracking, and overall matrix compactness. In the present study, the Rapid Chloride Penetration Test (RCPT) was used to evaluate the transport characteristics of basalt fiber reinforced recycled aggregate concrete at 90 days curing age.

4.3.1 Effect of Recycled Aggregate and Basalt Fiber on RCPT Values

The RCPT results, expressed as total charge passed in coulombs, are summarized in Figure 7. For all mixes, an increase in RCPT values was observed with increasing recycled aggregate content, indicating higher chloride ion penetrability associated with the more porous nature of recycled aggregate concrete. For mixes without basalt fiber reinforcement (BF = 0%), the RCPT charge passed increased from 2150 coulombs for the control mix to 3050 coulombs at 100% recycled aggregate replacement. All non-fiber mixes were classified under the *moderate chloride permeability* category according to ASTM criteria. The progressive increase in charge passed with recycled aggregate content confirms that the presence of adhered old mortar and microcracks enhances pore connectivity and facilitates ionic transport.

The incorporation of basalt fibers significantly reduced RCPT values across all recycled aggregate levels. At a fiber dosage of 0.2%**,** RCPT values decreased to the range of 1750–2550 coulombs, with mixes up to 25% recycled aggregate achieving *low chloride permeability*. However, at higher recycled aggregate contents, the permeability classification shifted back to *moderate*, indicating partial but insufficient mitigation of chloride transport at this fiber dosage.

The lowest RCPT values were consistently obtained in mixes containing 0.4% basalt fiber. At this dosage, RCPT values ranged from 1150 coulombs for the control mix to 1700 coulombs at 100% recycled aggregate replacement. All 0.4% fiber mixes fell within the *low chloride permeability* category, demonstrating a substantial reduction in ionic transport even at high recycled aggregate contents. This behaviour highlights the effectiveness of 0.4% basalt fiber in reducing microcrack continuity and improving pore discontinuity within the concrete matrix. Further increase in fiber dosage to 0.6% did not result in additional reduction in RCPT values. Although RCPT values for 0.6% fiber mixes **(**1350–2200 coulombs) were lower than those of non-fiber and 0.2% fiber mixes, they were consistently higher than those of 0.4% fiber mixes. In particular, mixes with 75% and 100% recycled aggregate at 0.6% fiber dosage shifted toward the upper range of *low permeability* and into *moderate permeability*. This trend suggests that excessive fiber content may adversely affect workability and matrix compactness, introducing additional voids that counteract the benefits of crack control. Overall, the RCPT results clearly demonstrate that basalt fiber reinforcement plays a significant role in enhancing resistance to chloride ion penetration in recycled aggregate concrete. An optimum basalt fiber dosage of 0.4% was identified as the most effective in reducing charge passed and achieving consistent *low chloride permeability* across all recycled aggregate replacement levels.

These findings are in strong agreement with the acid and sulphate durability results, confirming that optimized basalt fiber incorporation improves durability primarily by restricting microcrack development and reducing connectivity of transport pathways. Improved chloride resistance further supports the use of basalt fiber reinforced recycled aggregate concrete in durable and sustainable reinforced concrete applications.

The RCPT results obtained in this study are consistent with observations reported in earlier research on chloride transport in recycled aggregate and fiber reinforced concretes. Poon and Chan (2007) reported that recycled aggregate concrete generally exhibits higher chloride permeability due to the presence of adhered old mortar and increased pore connectivity, which aligns with the higher charge passed observed in non-fiber mixes in the present study. Silva, de Brito, and Dhir (2014) also highlighted that transport-related durability indicators such as RCPT are particularly sensitive to recycled aggregate content, especially at higher replacement levels. The significant reduction in charge passed achieved with basalt fiber incorporation agrees with findings by Guo et al. (2019), who reported that basalt fibers improve resistance to chloride ion penetration by limiting microcrack continuity and refining transport pathways. The optimum performance observed at 0.4% basalt fiber dosage further supports earlier conclusions that fiber content must be carefully optimized to achieve effective chloride resistance without adversely affecting matrix compactness.

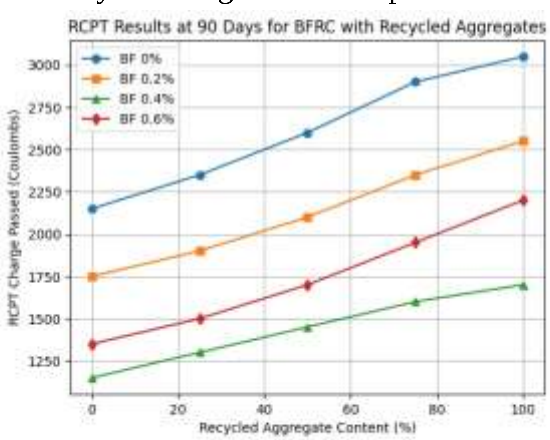


Figure 7. Effect of recycled aggregate content and basalt fiber dosage on RCPT charge passed at 90 days.

5. Conclusions

Based on the experimental investigation on the durability performance of basalt fiber reinforced recycled aggregate concrete of M20 grade, the following conclusions are drawn:

1. Acid attack using 5% sulphuric acid caused progressive deterioration in all mixes, with residual compressive strength decreasing as immersion duration increased from 28 to 90 days. Recycled aggregate concrete without fiber reinforcement showed higher vulnerability to acid exposure due to its more porous microstructure.
2. The incorporation of basalt fibers significantly improved resistance to acid attack at all recycled aggregate replacement levels. Among the investigated dosages, 0.4% basalt fiber consistently exhibited the highest residual compressive strength, indicating effective control of microcrack propagation and reduced acid ingress.
3. Sulphate attack using 5% magnesium sulphate resulted in gradual strength reduction with increasing exposure duration; however, the severity of deterioration was lower than that observed under acid attack. This confirms that sulphate attack is comparatively less aggressive for the investigated mixes.
4. Basalt fiber reinforcement enhanced sulphate resistance across all recycled aggregate levels. Mixes containing 0.4% basalt fiber demonstrated superior strength retention at 28, 56, and 90 days of sulphate exposure, even at higher recycled aggregate contents,

highlighting the role of fibers in delaying sulphate-induced damage.

5. Rapid Chloride Penetration Test results showed that chloride permeability increased with recycled aggregate content in non-fiber mixes, reflecting higher pore connectivity and transport potential. Basalt fiber addition significantly reduced RCPT charge passed values, indicating improved resistance to chloride ion penetration.
6. The lowest RCPT values and consistent "low permeability" classification were achieved at a basalt fiber dosage of 0.4%, confirming this dosage as optimum for enhancing transport-related durability. Higher fiber dosage (0.6%) did not provide additional benefit and, in some cases, resulted in increased charge passed due to possible workability and compaction issues.
7. Across all durability tests—acid attack, sulphate attack, and RCPT—the optimum performance was consistently obtained at 0.4% basalt fiber dosage. This demonstrates that durability enhancement through fiber reinforcement is dosage-dependent and requires optimization rather than maximum fiber addition.
8. The combined use of recycled aggregates and basalt fibers offers a viable approach to producing durable and sustainable concrete. Recycled aggregates contribute to conservation of natural resources, while basalt fibers mitigate durability limitations by restricting microcrack development and reducing ingress of aggressive agents.

Overall, the study confirms that basalt fiber reinforced recycled aggregate concrete, when properly optimized, can achieve improved durability performance under aggressive environmental conditions, supporting its application in sustainable construction with extended service life and reduced maintenance demand.

References

[1] P. K. Mehta and R. W. Burrows, "Building Durable Structures in the 21st Century," Concrete International, vol. 23, no. 3, pp. 57–63, 2001.

[2] V. M. Malhotra, "Role of supplementary cementing materials in reducing greenhouse gas emissions," Concrete International, vol. 26, no. 7, pp. 42–45, 2004.

[3] C. S. Poon and D. Chan, "The use of recycled aggregate in concrete in Hong Kong," Resources, Conservation and Recycling, vol. 50, no. 3, pp. 293–305, 2007, doi: 10.1016/j.resconrec.2006.06.005.

[4] J. Xiao, W. Li, and Y. Fan, "An overview of study on recycled aggregate concrete in China (1996–2011)," Construction and Building Materials, vol. 31, pp. 364–383, 2012, doi: 10.1016/j.conbuildmat.2011.12.074.

[5] A. Katz, "Properties of concrete made with recycled aggregate from partially hydrated old concrete," Cement and Concrete Research, vol. 33, no. 5, pp. 703–711, 2003, doi: 10.1016/S0008-8846(02)01033-5.

[6] B. González-Fonteboa and F. Martínez-Abella, "Recycled concrete with coarse recycled aggregate: An overview and

analysis," Materiales de Construcción, vol. 68, 2018.

[7] R. V. Silva, J. de Brito, and R. K. Dhir, "Use of recycled concrete aggregate in concrete: A review," 2014.

[8] C. J. Zega and D. A. Di Maio, "Durable Performance of Recycled Aggregate Concrete in Aggressive Environments: A Review," Journal of Materials in Civil Engineering (ASCE), 2020.

[9] E. K. Attiogbe and S. H. Rizkalla, "Response of Concrete to Sulfuric Acid Attack," ACI Materials Journal, vol. 85, no. 6, pp. 481–488, 1988.

[10] E. Hewayde, M. Nehdi, and E. Allouche, "Effect of Mixture Design Parameters and Wetting–Drying Cycles on Resistance of Concrete to Sulfuric Acid Attack," Journal of Materials in Civil Engineering (ASCE), vol. 19, no. 2, pp. 155–163, 2007.

[11] M. Santhanam, M. D. Cohen, and J. Olek, "Mechanism of sulfate attack: A fresh look. Part 1: Summary of experimental results," Cement and Concrete Research, 2002.

[12] M. Santhanam, M. D. Cohen, and J. Olek, "Mechanism of sulfate attack: A fresh look. Part 2: Proposed mechanisms," Cement and Concrete Research, 2002

[13] ASTM C1012/C1012M, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution," ASTM International, West Conshohocken, PA, 2018.

[14] ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 2012.

[15] K. H. Obla, "Concrete Resistant to Chloride Ion Penetration: Tests & Criteria," NRMCA, 2016.

[16] H. Meng, J. Wei, and L. Xing, "Permeability and mechanical properties of basalt fiber-reinforced concrete under magnesium sulfate corrosion," Revue des Composites et des Matériaux Avancés, vol. 28, pp. 333–343, 2018, doi: 10.3166/RCMA.28.333-343.

[17] Z. Algin and M. Ozen, "The properties of chopped basalt fibre reinforced self-compacting concrete," Construction and Building Materials, vol. 186, pp. 678–685, 2018

[18] Y. Guo, J. Xie, J. Zhao, and J. Zuo, "Experimental study on the resistance of basalt fibre concrete to chloride penetration," Construction and Building Materials, 2019.

[19] M. T. Bassuoni and M. L. Nehdi, "Durability of self-consolidating concrete to sulfate attack under combined cyclic environments and flexural loading," Cement and Concrete Research, vol. 39, no. 3, pp. 206–226, 2009, doi: 10.1016/j.cemconres.2008.12.003.

[20] L. Barcelo, J. Gartner, and E. J. C. et al., "A modified ASTM C1012 procedure for qualifying blended cements for sulfate exposure," Cement and Concrete Research, 2014.

[21] L. R. Santillán, F. Locati, Y. Villagrán-Zaccardi, and C. Zega, "Long-term sulfate attack on recycled aggregate concrete immersed in sodium sulfate solution for 10 years," Materiales de Construcción, 2020.

[22] R. Somna, C. Jaturapitakkul, P. Kajitvichyanukul, and P. Chindaprasirt, "Effect of water-to-binder ratio and ground

fly ash on properties of recycled aggregate concrete," Journal of Materials in Civil Engineering (ASCE), 2012.