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Evaluation of strength, wear, and skid resistance in pavement quality concrete with partial replacement of steel slag

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ABSTRACT

Sustainable pavement construction is essential for promoting ecological balance and reducing the environmental impact of infrastructure projects. This study investigates the viability of partially replacing conventional fine aggregate (river sand) with steel slag in proportions ranging from 10% to 100% by volume for pavement quality concrete (PQC). The mechanical properties of PQC were evaluated following IRC standards, with a focus on compressive strength, flexural strength, split tensile strength, and fatigue performance. Additionally, the study assessed the concrete's abrasion resistance and skid resistance, critical for ensuring durability and road safety. The experimental results demonstrated that incorporating steel slag as a fine aggregate replacement significantly enhances the mechanical performance of PQC. A mix containing 40% steel slag exhibited optimal improvements in compressive, flexural, and tensile strengths, alongside superior resistance to wear and skid. These findings indicate that steel slag, when used in appropriate proportions, can enhance both the durability and safety of concrete pavements. The study highlights the potential of steel slag as a sustainable and resource-efficient alternative to conventional materials in pavement construction, contributing to environmental sustainability and improved infrastructure performance.

Keywords: Pavement quality concrete; Steel slag; Sustainable; Skid resistance; Wear resistance.

1. INTRODUCTION

Sustainable pavement construction is crucial for infrastructure projects to promote long-term ecological balance and have as little of an impact on the environment as possible. Conventional pavement materials and methods frequently lead to increased greenhouse gas emissions, resource depletion, and excessive energy usage. We can minimize carbon footprints, increase the lifespan of pavements, and decrease waste by using sustainable practices, such as the use of recycled materials, energy-efficient procedures, and low-impact designs [1–3]. Building concrete roads is an important component of developing the global infrastructure, especially in industrialized countries like the United States, China, and Europe. Because concrete is durable and requires less maintenance during its lifetime, it is utilized for over 60% of highways and arterial roads worldwide [4–6]. Concrete roads are becoming more popular in India as the nation moves away from traditional bituminous roads, which still account for 90% of the country's road network. Using stronger materials like concrete, recent projects funded by the Pradhan Mantri Gram Sadak Yojana and the Bharatmala Pariyojana seek to improve road connectivity. In spite of the greater initial cost, India is moving more and more toward the use of concrete roads, especially for national highways and urban road projects [7, 8].

Utilizing industrial waste in concrete is an innovative and environmentally friendly approach that mitigates the impact of waste disposal and reduces the environmental footprint of the concrete industry. Concrete mixtures can incorporate materials such as fly ash, slag, silica fume, and even recycled aggregates from demolished structures. These waste byproducts not only enhance the strength, resilience, and workability of concrete but also reduce the need for virgin raw materials like cement, the production of which is energy-intensive and results in significant CO2 emissions. By recycling industrial waste into concrete, the construction sector promotes the principles of a circular economy, reducing resource depletion and minimizing landfill waste [9–15].

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The structural and environmental benefits of using steel slag, a byproduct of the steel industry, as an aggregate in concrete are increasingly being recognized. Steel slag enhances the mechanical properties and durability of concrete due to its high density and strength, allowing it to effectively replace natural aggregates. Additionally, the use of steel slag improves the concrete's resistance to chemical attack, alkali-silica reaction, and freeze-thaw cycles. Its incorporation also reduces the carbon footprint of concrete production and promotes sustainable construction practices by decreasing waste and the need for virgin resources [16].

The unique properties of steel slag give concrete enhanced mechanical characteristics. Concrete's compressive strength, tensile strength, and durability improve when steel slag partially replaces natural aggregates, especially during the later stages of curing. The high density and angularity of steel slag result in better binding strength between the aggregate and cement paste. Moreover, the inclusion of steel slag increases the concrete's resistance to impact, wear, and freeze-thaw cycles, making it suitable for high-stress environments [17]. From the literature review, research has been conducted on using steel slag as a substitute in concrete for building construction. However, limited studies are available on the use of steel slag in concrete for road construction, particularly in the Indian context. Specifically, there is a lack of research on the mechanical properties such as flexural strength and fatigue life, as well as durability characteristics like resistance to wear and skid resistance. Therefore, this research aims to evaluate the mechanical and durability characteristics of concrete used in road construction by replacing conventional fine aggregate with steel slag in varying proportions, from 10% to 100%, with increments of 10%, as outlined in the methodology below.

This literature explores sustainable pavement practices, focusing on using steel slag as a partial fine aggregate replacement in concrete for road construction. It evaluates mechanical and durability properties while addressing research gaps, particularly in the Indian context.

2. METHODOLOGY

The methodology of this research is illustrated in Figure 1. Based on the literature review, the research gap was identified, leading to the formulation of the objective of this study. Initially, the mix ratio for the conventional material was determined for M45 grade concrete, consisting of water, conventional fine aggregate (river sand), and coarse aggregate. Following this, mix ratios were established for varying the replacement of conventional fine aggregate (river sand) with steel slag, ranging from 0% to 100% in increments of 10%. To evaluate the

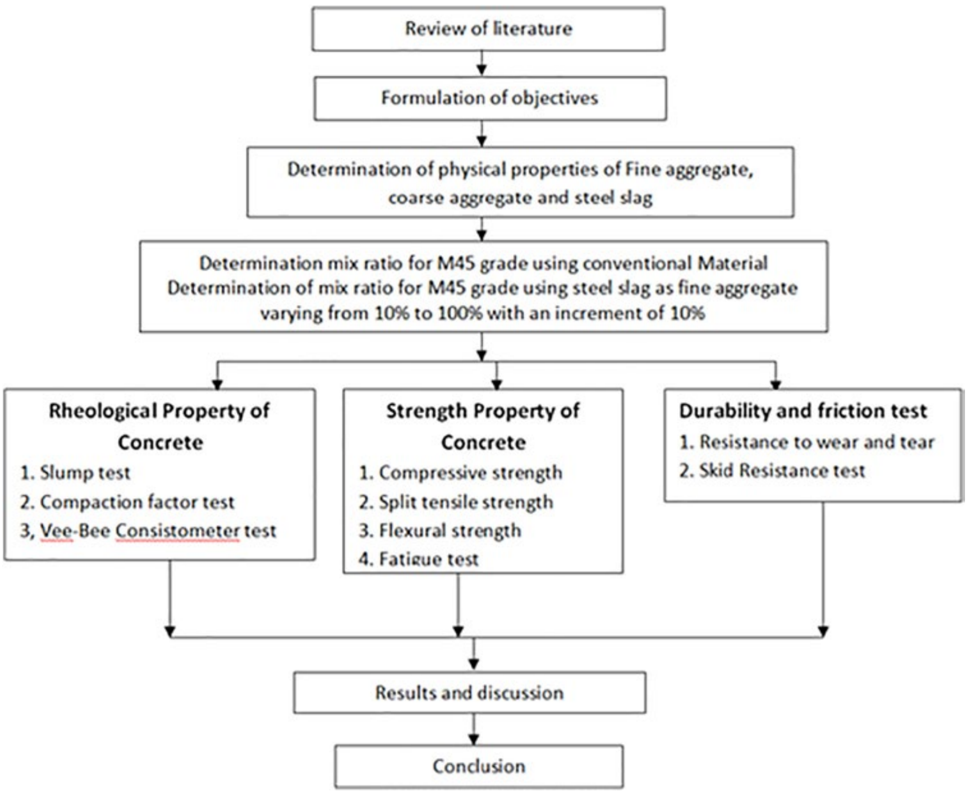

Figure 1: Grading curve of fine and coarse aggregate.

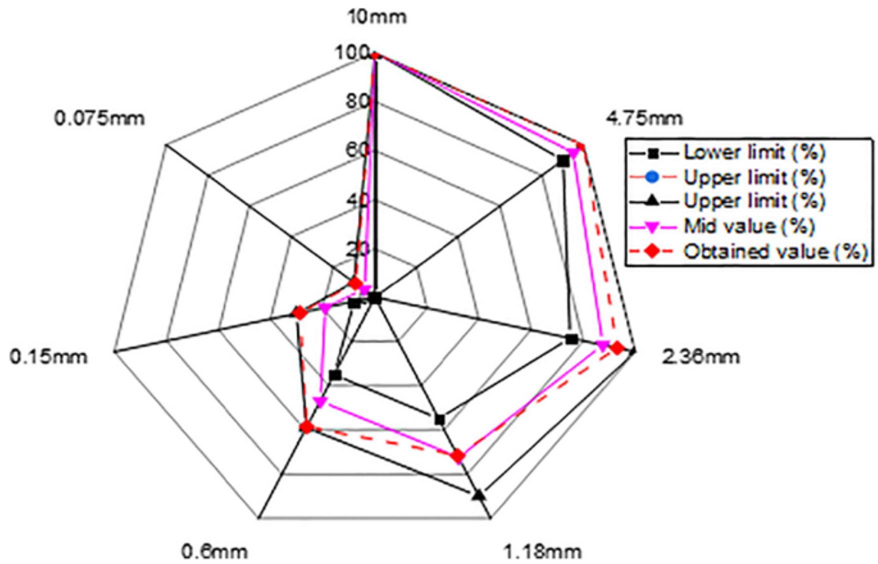

Figure 2: Conventional fine aggregate gradation satisfying the standard specification IRC 15-2017 and IRC 44-2017.

performance of these mixtures, several strength parameters were assessed, including compressive strength, flexural strength, and split tensile strength. Additionally, the rheological properties of the concrete were examined by measuring the slump value, compaction factor, and vee-bee time. Durability characteristics such as resistance to wear and skid resistance were also determined. The test results for the conventional mix and the various mixes with different proportions of steel slag were then compared to identify the optimal percentage of steel slag to be used as a partial replacement for fine aggregate in concrete.

3. MATERIALS AND MIX IDENTIFICATION

3.1. Materials

The materials used in this research include cement (Ordinary Portland Cement, OPC 53 grade), fine aggregate (natural river sand), steel slag (replacing fine aggregate in varying proportions from 10% to 100%, in increments of 10%), and coarse aggregate (crushed stone). The physical and chemical properties of the cement adhere to the standards specified in IS 269-2015. Both the fine aggregate (river sand) and coarse aggregate conform to the standard specifications of IRC 15-2017 and IRC 44-2017.

Figures 1 and 2 illustrate the particle size distribution of the conventional fine aggregate (river sand) and steel slag, respectively. The combined gradation of the conventional fine and coarse aggregates, in accordance with the requirements of IRC 15-2017 and IRC 44-2017, is shown in Figure 3. The steel slag used in this research was sourced from the steel industry and meets the particle size distribution standards outlined in IRC 15-2017 and IRC 44-2017. The steel slag samples employed in this study are depicted in Figures 4 and 5.

3.2. Mix identification

The various concrete mixes used in this research are designated as RX0, RX10, RX20, RX30, RX40, RX50, RX60, RX70, RX80, RX90, and RX100. In this naming convention, “R” stands for the concrete mix, while “X” denotes the percentage of steel slag used as a replacement for conventional fine aggregate (river sand). For instance, the RX0 mix represents concrete with 0% steel slag as fine aggregate, while the RX60 mix indicates a concrete mix with 60% steel slag as fine aggregate. This pattern is followed for the remaining mixes, with the percentage of steel slag increasing accordingly.

4. EXPERIMENTAL DETAILS

The rheological properties of the concrete were determined using the slump cone test, compaction test, and Vee-Bee test, in accordance with the standard specifications outlined in IS 1199 (Part 2 – 2018). The concrete strength parameters, including compressive strength and flexural strength, were evaluated based on the standard specifications of IS 516-2018. To prepare the fresh homogeneous concrete, a mixer machine was used, where the materials were mixed in the drum and rotated for a period of no less than 2 minutes. To assess the

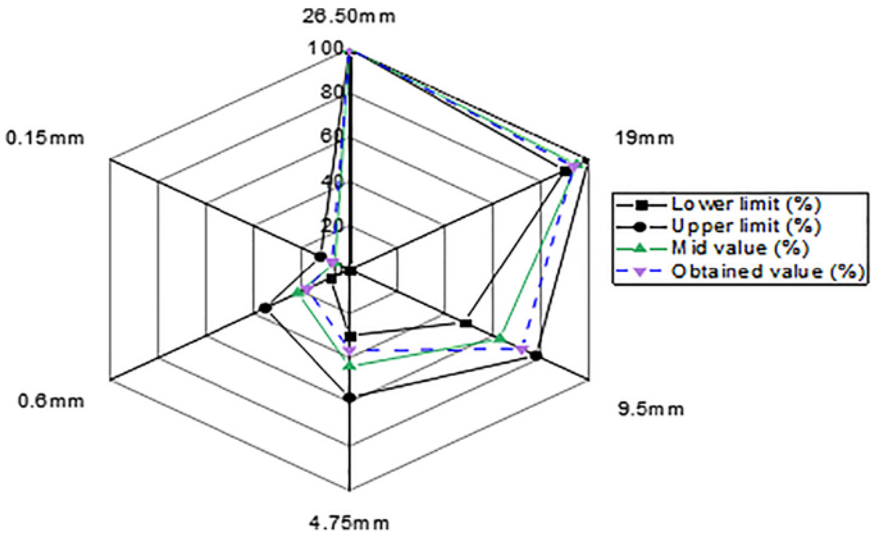

Figure 3: Combined gradation of Conventional Fine and coarse aggregate gradation satisfying the standard specification IRC 15-2017 and IRC 44-2017.

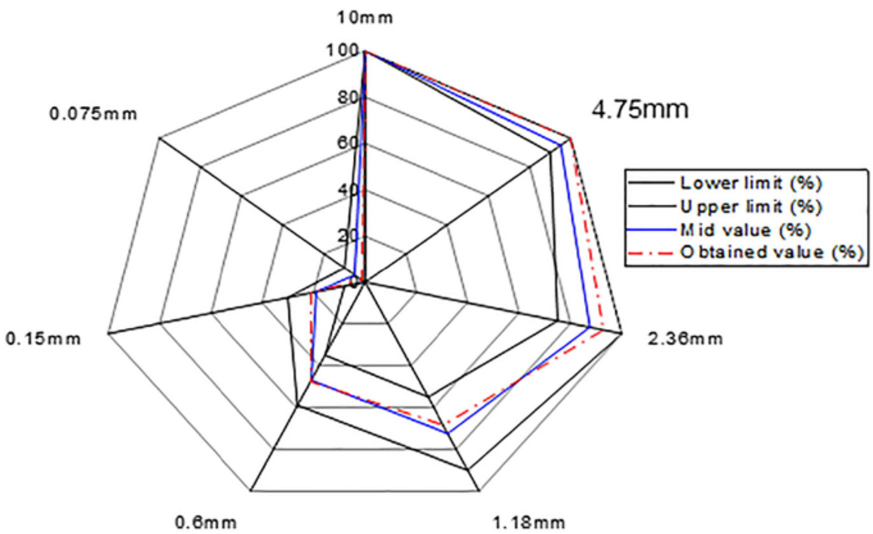

Figure 4: Combined gradation of Conventional Fine and coarse aggregate gradation satisfying the standard specification IRC 15-2017 and IRC 44-2017.

Figure 5: Graded Steel slag confirming to Zone 11 (IRC 15-2017 & IRC 44-2017).

compressive strength of the concrete, cube specimens measuring 150 mm × 150 mm × 150 mm were cast. For flexural strength testing, concrete prisms with dimensions of 150 mm × 150 mm × 700 mm, as per IRC 15-2017, were cast, and the experimental test setup is depicted in Figure 6(a). The split tensile strength of the concrete was measured in accordance with the specifications of IS 5816. The experimental setup for the split tensile strength test is shown in Figure 6(b). Additionally, cylindrical concrete specimens with a diameter of 15cm and a height of 30cm were cast following the specifications of IS: 10086-1982. The resistance of concrete to wear and tear due to abrasive action was determined according to IS 1237-2012. The abrasion resistance of the concrete cube specimens, sized 7.06 cm, was calculated by measuring the difference in height before and after the specimen was subjected to abrasion. The test setup for the abrasion resistance is shown in Figure 6(c). Figures 6(d) and 6(e) show the abraded specimens containing conventional fine aggregate and steel slag as fine aggregate, respectively. The abrasive resistance of the concrete was determined following the standard specification IS 9284-2002. The abrasive resistance of the concrete was measured as the difference in the mass loss of the specimen before and after being subjected to the abrasive action. The experimental setup for the abrasion test is shown in Figure 6(c). The mass loss indicates the degree of abrasion, providing insight into the material's resistance to wear over time. Figure 7 show the set of British pendulum.

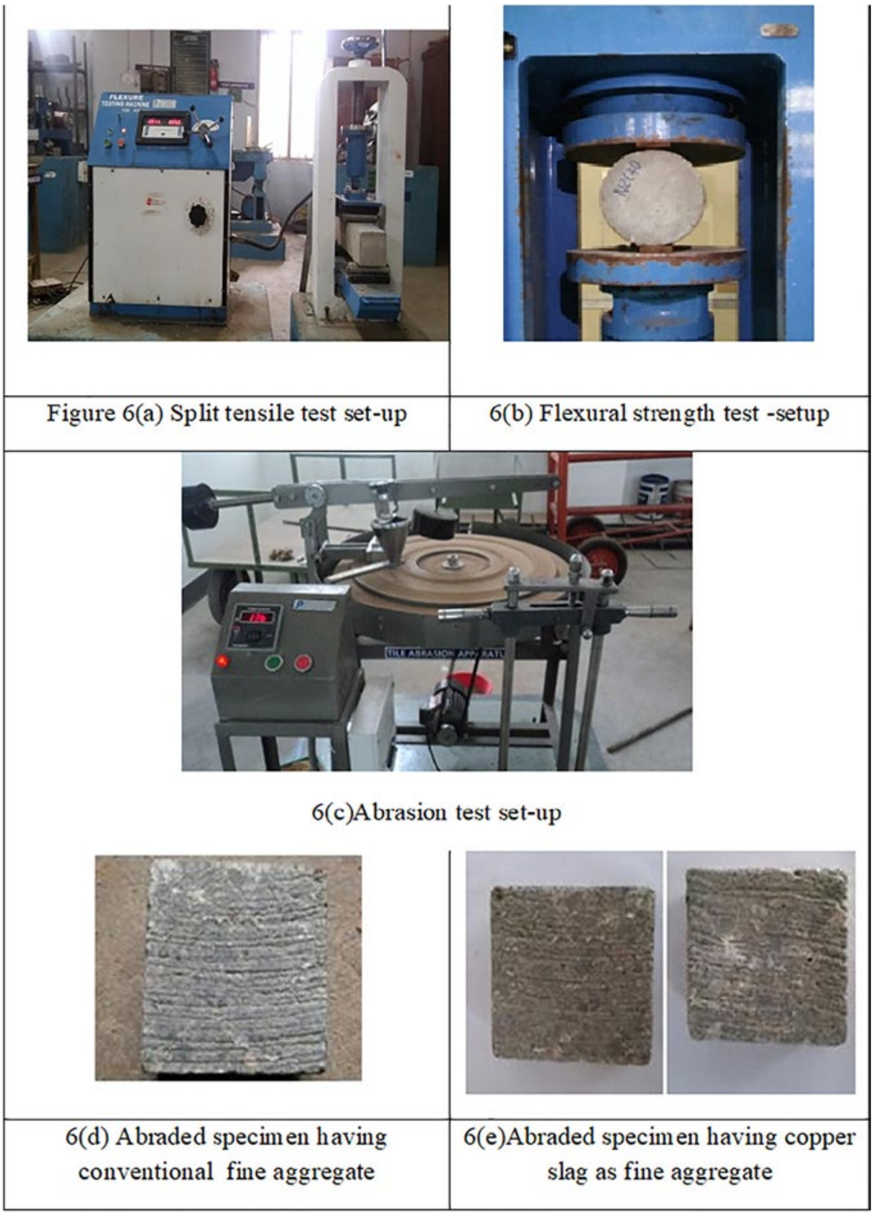

Figure 6: (a) Split tensile test set-up, (b) flexural strength test-setup, (c) abrasion test set-up, (d) abraded specimen having conventional fine aggregate, (e) abraded specimen having copper slag as fine aggregate.

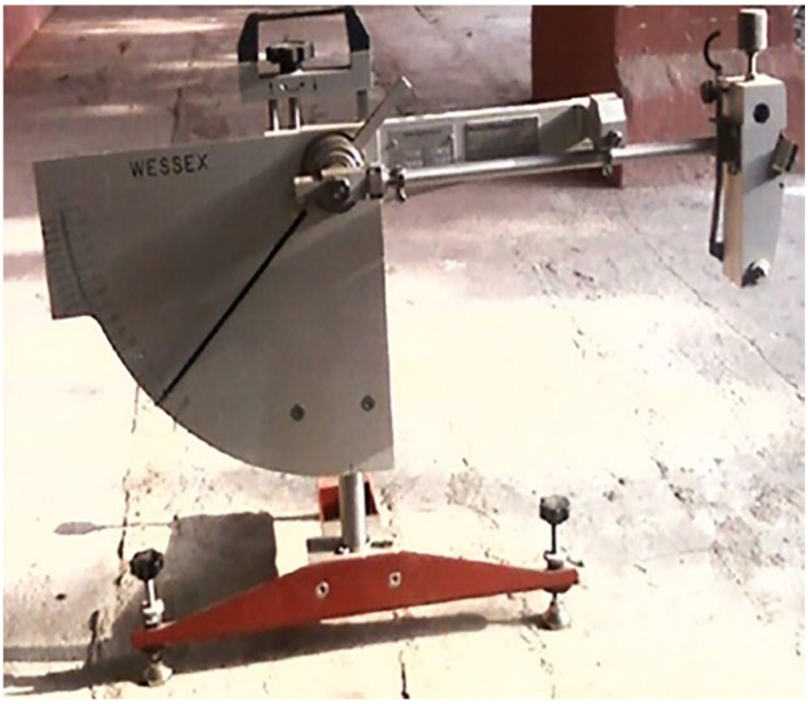

Figure 7: British pendulum tester (skid resistance tester).

5. RESULT AND DISCUSSION

5.1. Rheological characteristics

The consistency of the concrete was observed to increase with the rise in the dosage of steel slag as fine aggregate across all rheological tests, including the slump test, compaction factor test, and Vee-Bee test conducted on the fresh concrete. As shown in Figure 8, there was a gradual increase in the consistency of fresh concrete up to a 40% replacement of conventional fine aggregate with steel slag. Beyond the 40% replacement level, a sharp rise in the consistency of the fresh concrete was noted. This trend continued, with a more gradual increase in consistency thereafter. A similar pattern was observed in the other two consistency tests, the compaction factor test and the Vee-Bee time test, as illustrated in Figure 9. The angular and rough texture of steel slag particles is responsible for the steady increase in the consistency of fresh concrete with up to 40% inclusion of steel slag as fine aggregate. These characteristics facilitate better particle interlocking, which improves the cohesiveness and uniform distribution of the concrete mix, contributing to its stable consistency. As the proportion of steel slag increases, the concrete mix becomes denser. The porous nature of steel slag allows it to retain more water, helping to maintain balanced workability [18]. However, when the replacement of natural fine aggregate with steel slag exceeds 40%, there is a marked increase in consistency. The highly angular and rough surface of the slag particles at higher percentages demands more water for lubrication and dispersion, leading to reduced workability and a significant rise in mix viscosity. This imbalance accounts for the abrupt increase in consistency beyond the 40% threshold, resulting in a stiffer and less workable concrete mix [19].

Once the inclusion of steel slag exceeds 80% as fine aggregate, the increase in the consistency of fresh concrete becomes more gradual. This could be because the mix reaches a point where the addition of more slag has a diminishing effect on particle interaction. At higher levels, the physical properties of steel slag, such as its density and water-absorbing capacity, begin to counterbalance the effects of increased slag content, leading to a more controlled and gradual change in consistency [20].

The significant correlation observed between the compaction factor, slump value, and Vee-Bee time for concrete containing steel slag as fine aggregate is primarily influenced by the physical characteristics of steel slag and their impact on the workability of concrete. The angular shape and abrasive texture of steel slag increase internal friction between particles, directly affecting the ease with which the concrete compacts and flows. The slump value measures the flowability of concrete, while the compaction factor assesses how well the concrete consolidates under its own weight. The Vee-Bee time reflects the effort required to fully compact the

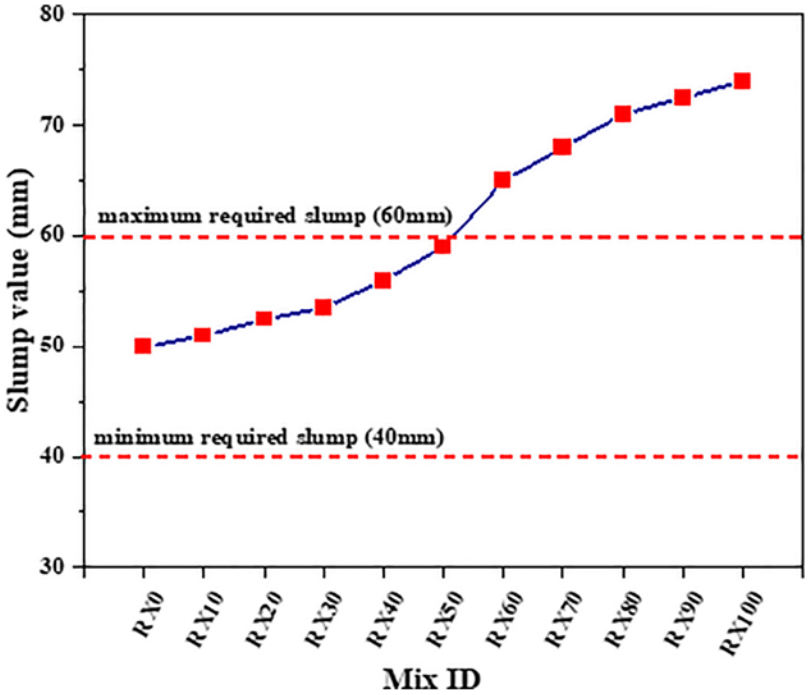

Figure 8: Variation of slump value for the different dosage of steel slag as fine aggregate.

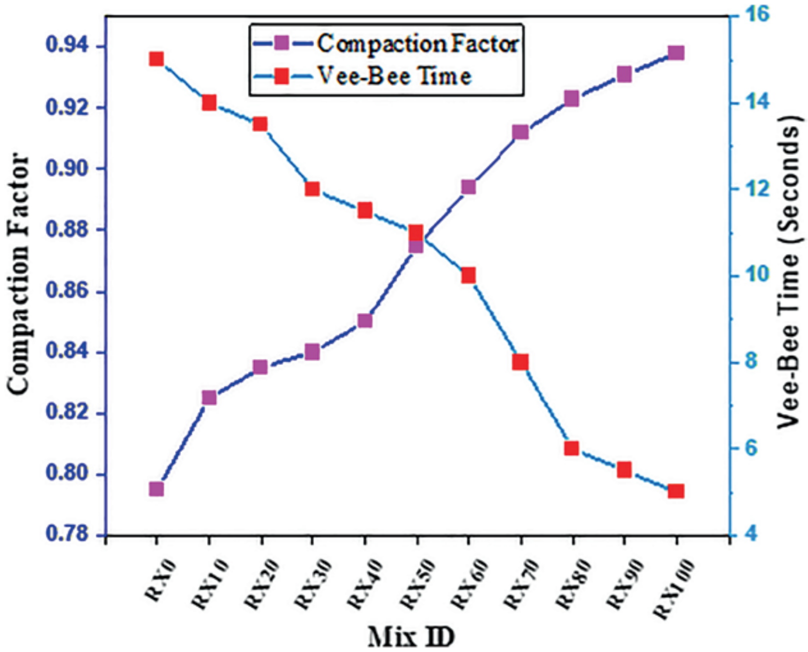

Figure 9: Variation of compaction factor value and Vee-Bee time for the different dosage of steel slag as fine aggregate.

concrete [21]. As the proportion of steel slag increases, the higher particle friction and reduced smoothness result in lower slump values, indicating increased resistance to flow. Consequently, the compaction factor decreases as the concrete becomes less self-consolidating. Simultaneously, the Vee-Bee time increases, indicating that more effort or time is required to adequately compact the concrete. The slump value, compaction factor, and Vee-Bee time exhibit similar responses to changes in the cohesiveness and workability of the mix, with these alterations being directly influenced by the addition of steel slag as fine aggregate [22]. The strong relationship between the slump value, compaction factor, and Vee-Bee time is illustrated in Figures 10, 11, and 12, respectively.

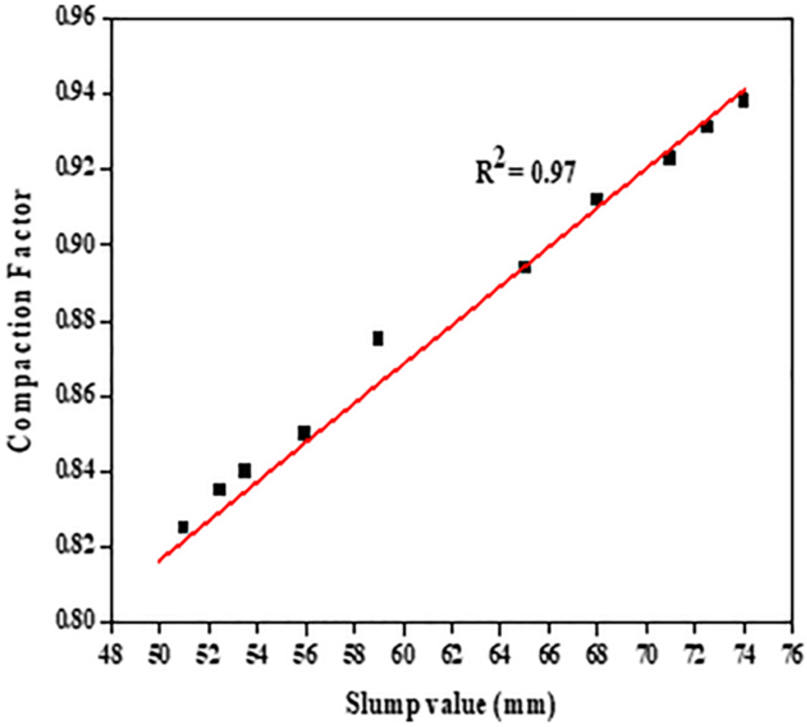

Figure 10: Relationship between the compaction factor and slump value (mm) for the different dosage of steel slag as fine aggregate.

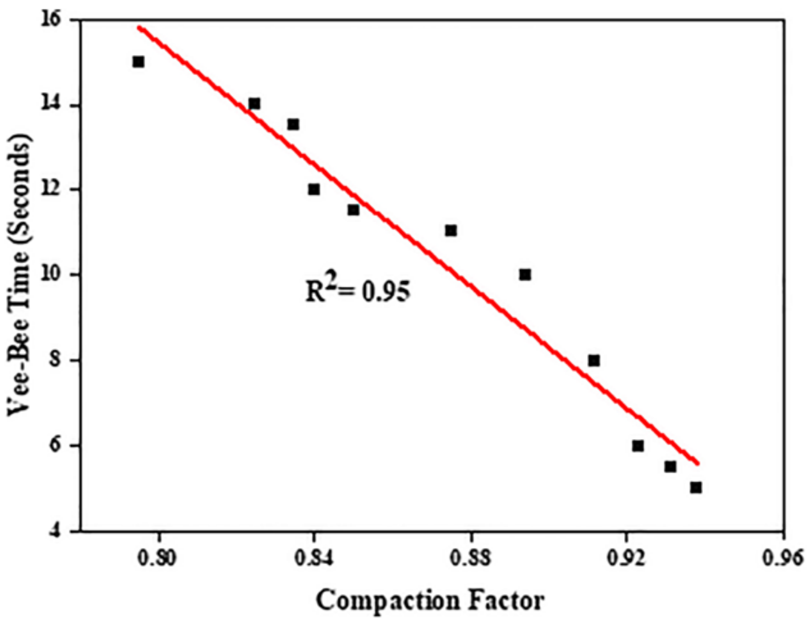

Figure 11: Relationship between the compaction factor and Vee-Bee time (seconds) for the different dosage of steel slag as fine aggregate.

5.2. Strength characteristics

The variation in compressive strength with the replacement of conventional fine aggregate (river sand) by steel slag in different mixes is illustrated in Figure 13. It was observed that compressive strength increased with the percentage of steel slag used as fine aggregate up to a 40% replacement. This trend was also noted for split tensile strength and flexural strength, as shown in Figures 14 and 15, respectively. This improvement in strength can be attributed to the presence of calcium silicates in the steel slag, which enhances the formation

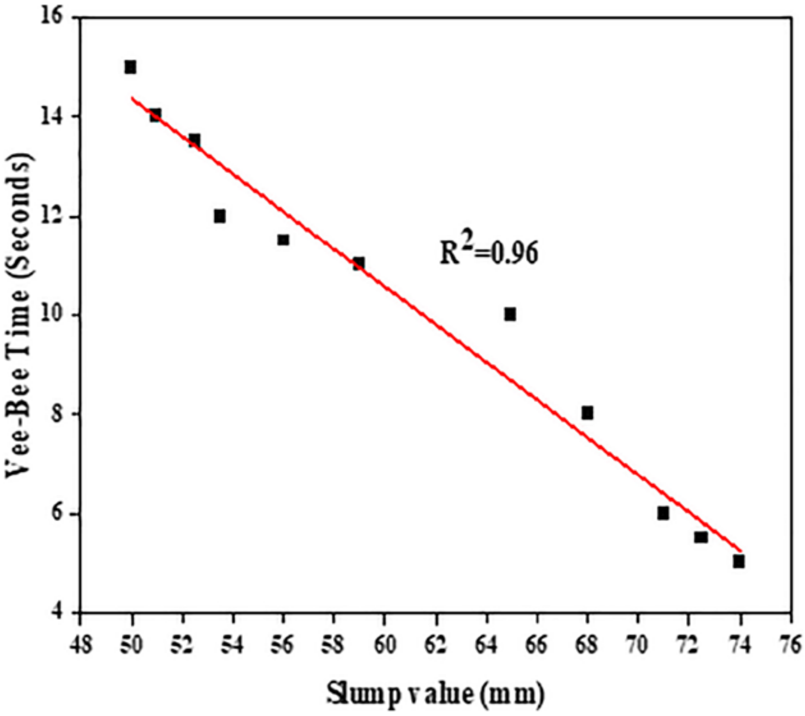

Figure 12: Relationship between the Vee-Bee time (seconds) and slump value (mm) for the different dosage of steel slag as fine aggregate.

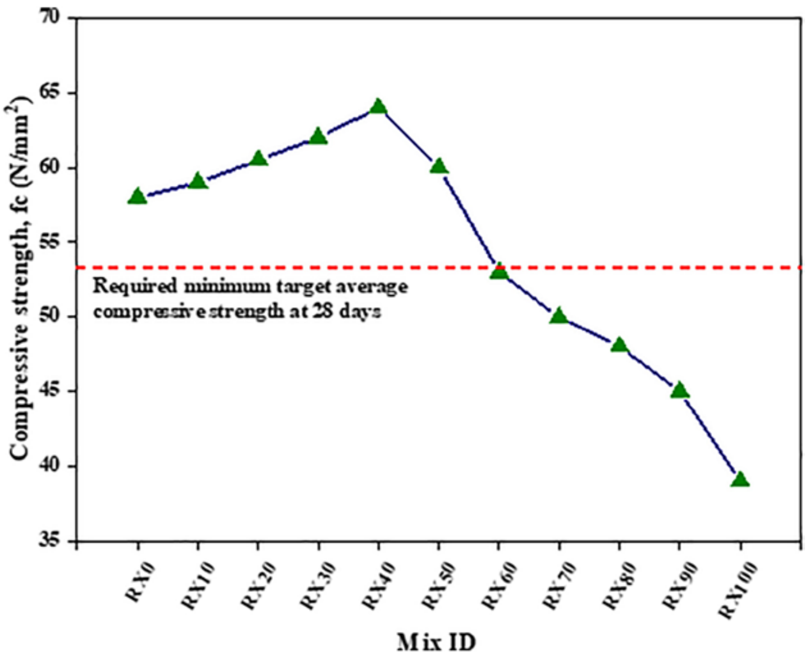

Figure 13: Variation of compressive strength for the different dosage of steel slag as fine aggregate.

of calcium-silicate-hydrate (C-S-H) gel in the concrete mix, contributing to higher strength [22]. The concrete becomes denser due to the fine particle size distribution of steel slag, which effectively fills the gaps between coarser aggregates. This reduces the development of microcracks, leading to increased compressive, flexural, and split tensile strengths up to a 40% replacement of conventional fine aggregate with steel slag [23]. However, beyond a 40% replacement, a decrease in compressive strength, flexural strength, and split tensile

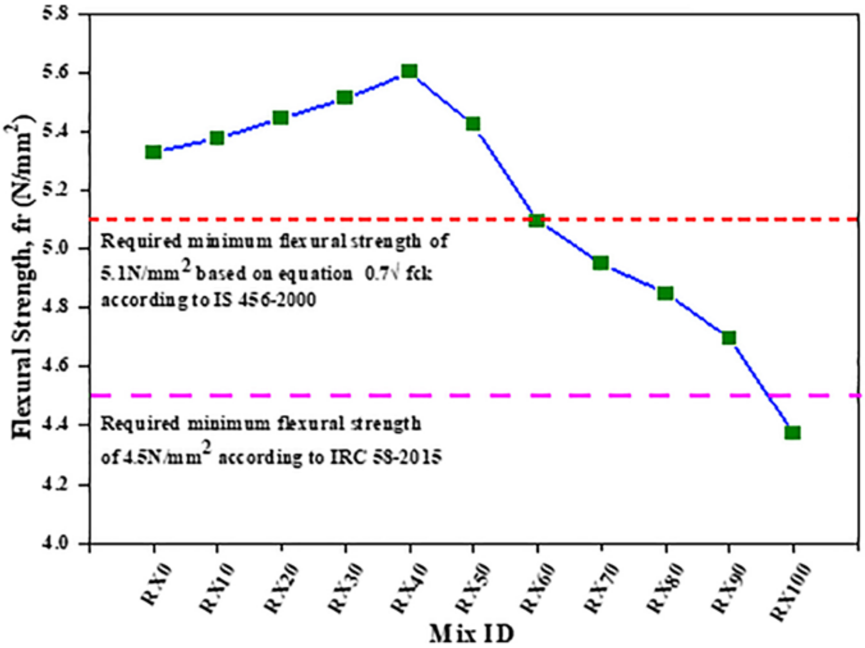

Figure 14: Variation of flexural strength for the different dosage of steel slag as fine aggregate.

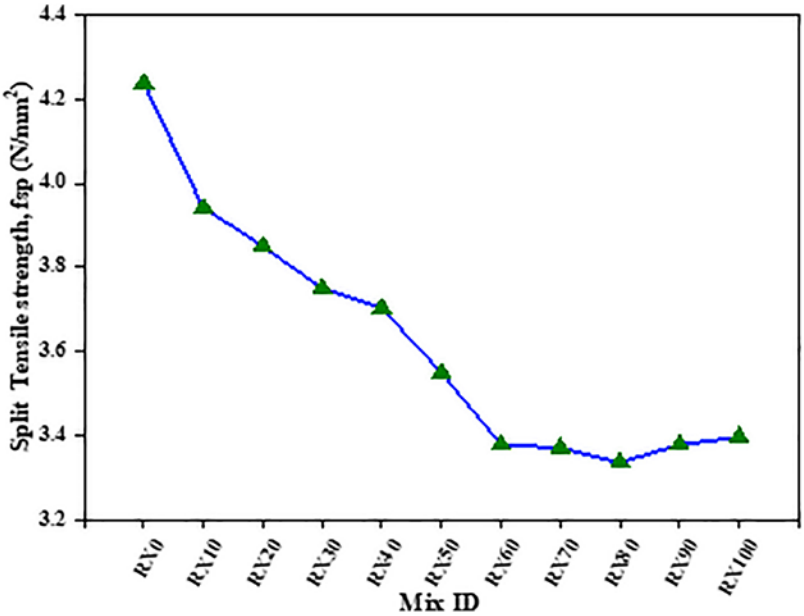

Figure 15: Variation of split tensile strength for the different dosage of steel slag as fine aggregate.

strength was observed. This decline can be attributed to several factors. At higher dosages, the rough texture and angular shape of steel slag, which initially provide better interlocking and enhance strength, can impair consistency and compaction, leading to reduced strength characteristics [24]. Additionally, the higher specific gravity of steel slag compared to other concrete ingredients can cause segregation, further reducing strength at higher dosages [25]. Furthermore, higher dosages of steel slag result in a greater concentration of CaO and MgO, which are expansive over time and can cause internal stresses in the concrete. This contributes to the development of microcracks and a considerable reduction in compressive, flexural, and split tensile strengths [26]. The variation in fatigue life for different dosages of steel slag as fine aggregate in pavement quality concrete is depicted in Figure 16. Fatigue life increases with the dosage of steel slag up to a 40% replacement of conventional fine aggregate. Beyond this point, the trend in fatigue life mirrors the observed reductions in compressive, flexural, and split tensile strengths, showing a decline as the dosage exceeds 40%.

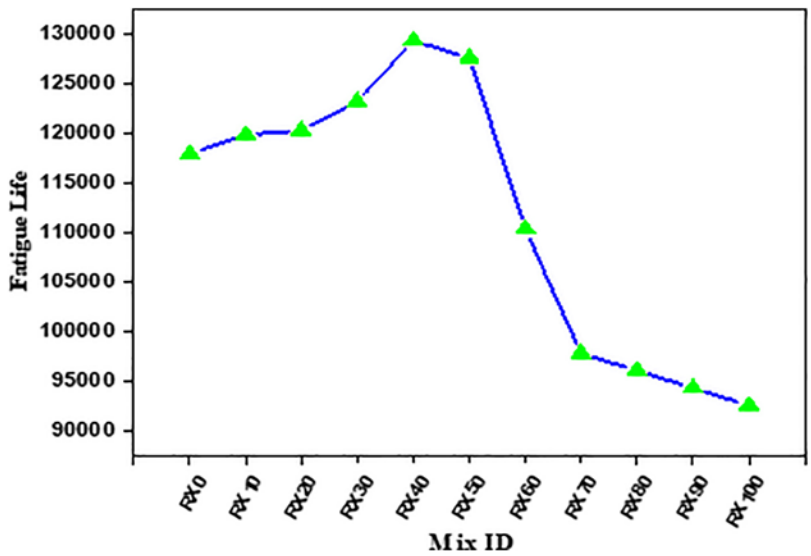

Figure 16: Variation of fatigue life for the different dosage of steel slag as fine aggregate.

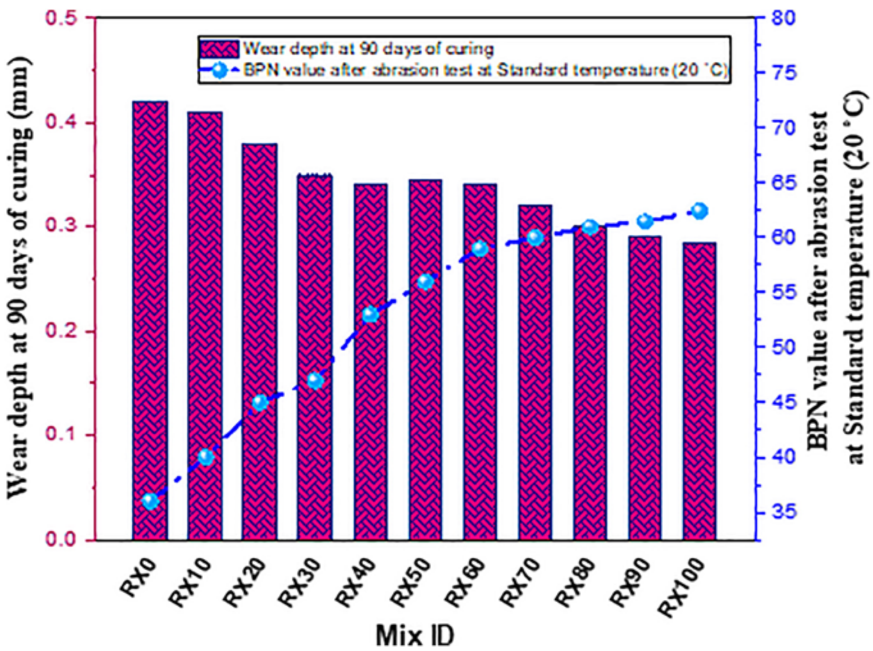

Figure 17: Variation of wear resistance subjected to abrasive action and corresponding BPN value for the different dosage of steel slag as fine aggregate.

5.3. Wear resistance and skid value

The Variation of wear resistance subjected to abrasive action and corresponding BPN value for the different dosage of steel slag as fine aggregate are shown in Figures 17 and 18 respectively. It was noted, that the abrasive resistance and skid resistance increase steeply with increase in dosage of steel slag as fine aggregate up to 40% dosage of steel slag, beyond 40% replacement gradual increase was noted. The main reason steel slag increases the resistance to abrasion in concrete is because it is a rough-textured, extremely durable, and hard substance that strengthens the mechanical strength of concrete. Because of its coarse and angular particles, the concrete matrix interlocks well, increasing the material's toughness and resistance to wear. The addition of steel slag results in a denser microstructure, which lowers porosity and increases surface resistance to abrasion. Concrete that combines these better particle packing and mechanical qualities is more resistant to abrasive forces [27]. The rough and angular texture of the steel slag particles is the main reason for the increase in skid resistance

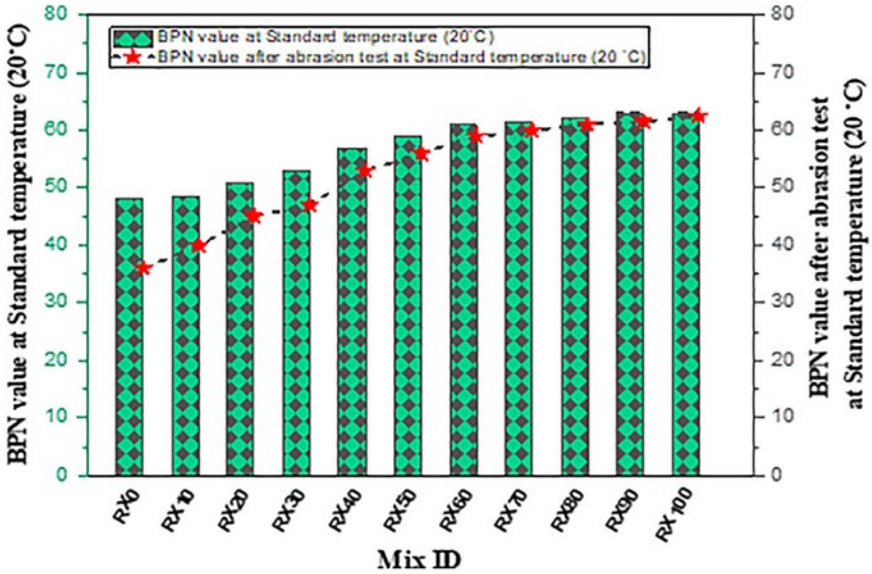

Figure 18: Variation of BPN value before and after subjected to abrasion for the different dosage of steel slag as fine aggregate.

that occurs when steel slag is added to concrete. Increased friction between tires and the concrete pavement due to this rougher surface improves skid resistance. Furthermore, the porous structure of steel slag could aid in improved water drainage, which would increase the surface's resistance to skidding, particularly in damp circumstances [28–31].

6. CONCLUSION

This experimental study reveals that substituting conventional fine aggregate (natural river sand) with steel slag in concrete results in significant improvements in both rheological and strength properties, as well as enhanced wear and skid resistance. The consistency of the concrete, evaluated using the slump test, compaction factor, and Vee-Bee test, shows noticeable improvement as steel slag is incorporated. The optimal performance is observed with up to 40% replacement of river sand by steel slag. This improvement is primarily attributed to the rough and angular texture of steel slag particles, which enhances interlocking between the aggregates, thereby improving the workability and compatibility of the concrete mix.

Strength-wise, the compressive, flexural, and split tensile strengths of the concrete increase with steel slag replacement up to 40%. This improvement is likely due to the presence of calcium silicates in the steel slag, which contribute to the formation of additional cementitious compounds, and better particle packing, which enhances the concrete's overall density and bonding capacity. However, when the steel slag content exceeds 40%, a decline in strength is observed. This reduction can be attributed to the decreased workability of the concrete, leading to segregation of the aggregates and the formation of micro-cracks. The excessive steel slag disrupts the homogeneity of the mix, resulting in poor cohesion and a weaker concrete matrix.

In terms of durability, abrasion and skid resistance show similar trends to the strength results. The incorporation of steel slag up to 40% significantly enhances these properties, which is crucial for concrete pavement applications. The rough texture and durability of the steel slag improve the concrete's resistance to wear and friction, making it more resistant to the high stress and load-bearing demands of wheel traffic. However, beyond 40% replacement, the benefits begin to diminish, as the impaired workability and potential micro-cracking weaken the surface layer of the concrete, reducing its wear resistance.

Overall, replacing up to 40% of the fine aggregate with steel slag provides an optimal balance, significantly improving the concrete's strength, durability, and skid resistance, making it particularly suitable for pavement applications. Beyond this threshold, the drawbacks of excessive steel slag outweigh its benefits, emphasizing the need to optimize the replacement level for the best performance.

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