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Utilization of Recycled Aggregates in Concrete: Mechanical Properties and Long-Term Performance

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Abstract:
The utilization of recycled aggregates in concrete has emerged as a promising strategy to mitigate the environmental impact of construction activities while addressing the growing demand for sustainable building materials. This research investigates the mechanical properties and long-term performance of concrete incorporating varying proportions of recycled aggregates. Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I was used as the primary binder, with recycled aggregates sourced from local demolition waste. Six concrete mixes were prepared with replacement levels of 0%, 25%, 50%, 75%, and 100% by volume of natural aggregates with recycled aggregates, alongside a control mix with 100% natural aggregates. The study evaluated compressive strength, tensile strength, flexural strength, permeability, drying shrinkage, and freeze-thaw resistance of the concrete mixes at 7, 28, and 90 days. Results indicate that while lower replacement levels demonstrated comparable mechanical properties to conventional concrete, higher proportions of recycled aggregates led to reductions in strength and increased permeability and shrinkage. Recommendations include optimizing aggregate processing techniques, refining mix designs with supplementary cementitious materials, implementing stringent quality control measures, conducting long-term field studies, and advocating for standardized guidelines to promote the sustainable use of recycled aggregates in concrete construction.

Keywords: Recycled aggregates, Concrete, Mechanical properties, Durability, Sustainable Construction.

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الاستفادة من الركام المعاد تدويره في الخرسانة: الخواص الميكانيكية والأداء طويل المدى

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الملخص
لقد ظهر استخدام الركام المعاد تدويره في الخرسانة كاستراتيجية واعدة للتخفيف من الأثر البيئي لأنشطة البناء مع تلبية الطلب المتزايد على مواد البناء المستدامة. تبحث هذه الورقة في الخواص الميكانيكية والأداء طويل المدى للخرسانة التي تتضمن نسبًا مختلفة من

الركام المعاد تدويره. تم استخدام الأسمنت البورتلاندي العادي (OPC) المطابق للمواصفة ASTM C150 Type I كمادة رابطة أولية، مع الحصول على الركام المعاد تدويره من نفايات الهدم المحلية. تم تحضير ستة خلطات خرسانية بمستويات استبدال 0%، 25%، 50%، 75%، و100% من حيث الحجم من الركام الطبيعي مع الركام المعاد تدويره، إلى جانب خلطة السيطرة مع الركام الطبيعي 100%. تم في هذه الدراسة تقييم مقاومة الضغط، مقاومة الشد، مقاومة الانثناء، النفاذية، انكماش الجفاف، ومقاومة التجمد والذوبان للخلطات الخرسانية عند 7، 28، و90 يوماً. تشير النتائج إلى أنه في حين أظهرت مستويات الاستبدال المنخفضة خصائص ميكانيكية مماثلة للخرسانة التقليدية، فإن النسب الأعلى من الركام المعاد تدويره أدت إلى انخفاض في القوة وزيادة النفاذية والانكماش. وتشمل التوصيات تحسين تقنيات معالجة الركام، وتحسين تصاميم الخلطات باستخدام مواد أسمنتية تكميلية، وتنفيذ تدابير صارمة لمراقبة الجودة، وإجراء دراسات ميدانية طويلة الأجل، والدعوة إلى مبادئ توجيهية موحدة لتعزيز الاستخدام المستدام للركام المعاد تدويره في البناء الخرساني.

الكلمات المفتاحية: الركام المعاد تدويره، الخرسانة، الخواص الميكانيكية، المتانة، البناء المستدام.

Introduction

The construction industry is a major consumer of natural resources and a significant contributor to environmental degradation. According to the Global Status Report for Buildings and Construction 2019 by the International Energy Agency (IEA), the building sector was responsible for 36% of global final energy consumption and nearly 40% of total direct and indirect CO_2 emissions in 2018 [1]. One of the primary materials used in construction is concrete, which relies heavily on natural aggregates. Natural aggregates, such as sand, gravel, and crushed stone, are obtained from quarries and riverbeds, leading to habitat destruction, resource depletion, and significant environmental impact. In light of these challenges, the use of recycled aggregates derived from construction and demolition (C&D) waste has gained considerable attention. Recycled aggregates are produced by crushing and processing concrete debris from demolished structures. These aggregates can be reused in new concrete production, thereby reducing the demand for natural aggregates and minimizing C&D waste [2]. The adoption of recycled aggregates aligns with sustainable construction practices by promoting resource efficiency, reducing environmental footprint, and supporting waste management initiatives.

The primary objectives of this research are threefold: to investigate the mechanical properties of concrete containing varying proportions of recycled aggregates, to assess the long-term performance and durability of recycled aggregate concrete, and to provide practical recommendations for the optimization of mix design and processing techniques. By understanding how recycled aggregate content influences compressive strength, tensile strength, and flexural strength, the study aims to determine the viability of using recycled materials in structural applications. Additionally, evaluating the long-term performance of recycled aggregate concrete, including parameters such as permeability, shrinkage, and resistance to freeze-thaw cycles, will help identify potential limitations or benefits associated with recycled aggregate use. The findings will assist engineers and construction professionals in implementing sustainable practices without compromising structural integrity.

The significance of utilizing recycled aggregates in concrete cannot be overstated. The construction industry generates a substantial amount of C&D waste annually, contributing to landfill overuse and environmental pollution. For example, the European Union reported that C&D waste accounts for approximately 25-30% of all waste generated in the region [3]. In the United States, the Environmental Protection Agency (EPA) estimated that 600 million tons of C&D debris were generated in 2018, with concrete constituting a significant portion of this waste [4]. Incorporating recycled aggregates in concrete production offers several environmental and economic benefits, including resource conservation, waste reduction, and potential cost savings. By reusing materials from demolished structures, the demand for natural aggregates is reduced, preserving natural resources and decreasing the environmental impact of quarrying activities. Utilizing C&D waste as a resource for new construction materials helps divert debris from landfills, contributing to more efficient waste management practices. Additionally, recycled aggregates can be more cost-effective than natural aggregates, particularly in regions where natural resources are scarce or expensive, resulting in significant cost savings for construction projects.

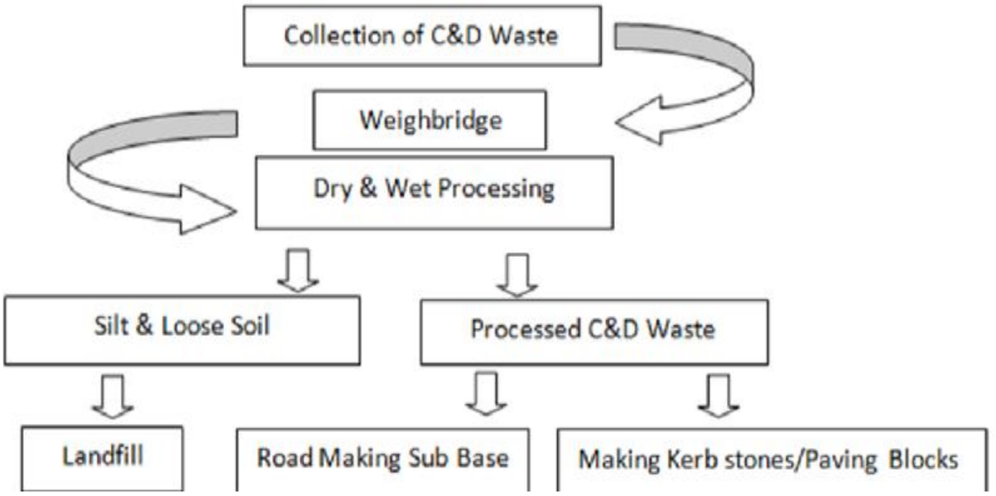

Figure 1 The production process of recycled aggregates from demolition waste. [15]

Previous studies have highlighted both the potential and challenges associated with the use of recycled aggregates in concrete. For instance, the American Concrete Institute (ACI) and the RILEM Technical Committee have published guidelines and specifications for the use of recycled aggregates in concrete, emphasizing the importance of quality control and appropriate mix design [5][6]. Research by Kou and Poon (2009) demonstrated that concrete prepared with recycled aggregates could achieve comparable mechanical properties to conventional concrete, provided that the recycled aggregates were of high quality and the mix design was optimized [7]. However, there are concerns regarding the variability in the properties of recycled aggregates, which can affect the consistency and performance of recycled aggregate concrete. The presence of adhered mortar, contaminants, and variability in aggregate size and quality can influence the mechanical properties and durability of the final product [8]. Therefore, further research is needed to address these challenges and develop standardized practices for the use of recycled aggregates in concrete.

Recycled aggregates are derived from the processing of construction and demolition (C&D) waste, which includes materials from the demolition of buildings, roads, bridges, and other structures. The processing involves crushing, screening, and sometimes washing to produce aggregates that can be used in new concrete mixes. These aggregates consist of a mix of natural aggregates and adhered mortar, which can affect their properties. According to Tam et al. (2005), the quality of recycled aggregates can vary significantly based on the source and processing methods used [2]. The presence of contaminants, such as brick, glass, or asphalt, can further influence the performance of recycled aggregate concrete.

Mechanical Properties of Recycled Aggregate Concrete

The mechanical properties of concrete, including compressive strength, tensile strength, and flexural strength, are critical for its structural performance. Numerous studies have investigated the effects of incorporating recycled aggregates on these properties. Research by Kou and Poon (2009) demonstrated that concrete prepared with recycled aggregates could achieve mechanical properties comparable to those of conventional concrete, provided that the recycled aggregates were of high quality and the mix design was optimized [7]. However, the compressive strength of recycled aggregate concrete generally tends to decrease with increasing recycled aggregate content. This reduction is attributed to the weaker adhered mortar and the potential presence of impurities in the recycled aggregates. Yang and Du (2011) observed that the compressive strength of concrete with 100% recycled aggregates could be 20-30% lower than that of conventional concrete [9]. Tensile and flexural strengths are also affected, but the extent of the reduction varies depending on the quality of the recycled aggregates and the mix design. Xiao et al. (2012) reported that the tensile strength of recycled aggregate concrete was generally within 10-15% of that of conventional concrete when high-quality recycled aggregates were used [8].

The durability of concrete is essential for ensuring the longevity and safety of structures. Factors such as permeability, shrinkage, and resistance to freeze-thaw cycles play a crucial role in the long-term performance of concrete. Recycled aggregate concrete has been shown to exhibit increased permeability and shrinkage compared to conventional concrete, primarily due to the porous nature of the adhered mortar and the presence of micro-cracks. However, freeze-thaw resistance is less consistently affected. Poon and Chan (2007) found that the freeze-thaw resistance of recycled

aggregate concrete could be comparable to that of conventional concrete if the recycled aggregates were of good quality and the mix design was properly adjusted [10]. The study by Gómez-Soberón (2002) further supports this, indicating that proper processing and treatment of recycled aggregates can mitigate the adverse effects on durability [11].
Various organizations have developed standards and guidelines to facilitate the use of recycled aggregates in concrete. The American Concrete Institute (ACI) and the RILEM Technical Committee have published recommendations that emphasize the importance of quality control and appropriate mix design. ACI Committee 555 (2002) provides guidelines for the removal and reuse of hardened concrete, outlining the necessary steps to ensure the quality and performance of recycled aggregates [12]. Similarly, the RILEM Technical Committee 121-DRG (1994) specifies the requirements for using recycled aggregates in concrete, focusing on aspects such as grading, contamination levels, and mechanical properties [13].
The environmental and economic benefits of using recycled aggregates in concrete are significant. By reducing the demand for natural aggregates, the environmental impact of quarrying activities is minimized, leading to the conservation of natural resources. Additionally, the use of recycled aggregates helps divert C&D waste from landfills, contributing to more efficient waste management practices. According to a study by Pacheco-Torgal et al. (2013), the incorporation of recycled aggregates can result in cost savings for construction projects, particularly in regions where natural aggregates are scarce or expensive [14]. These benefits align with the principles of sustainable construction, promoting resource efficiency and reducing the overall environmental footprint of construction activities.
Despite the potential benefits, there are several challenges associated with the use of recycled aggregates in concrete. The variability in the properties of recycled aggregates, such as grading, shape, and the presence of impurities, can affect the consistency and performance of recycled aggregate concrete. The durability of recycled aggregate concrete in aggressive environments, such as exposure to chlorides and sulfates, requires further investigation. Future research should focus on developing standardized practices for the production and use of recycled aggregates, optimizing mix designs to enhance mechanical properties and durability, and conducting long-term field studies to validate laboratory findings.

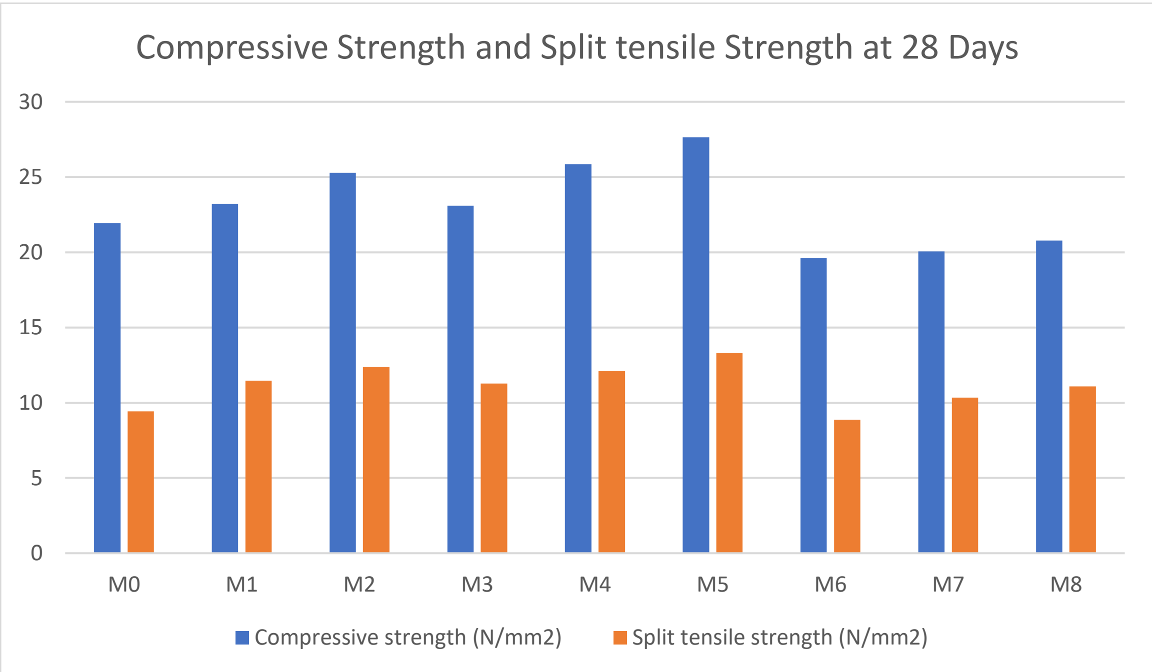

Figure 2 Mechanical properties (compressive strength, tensile strength, etc.) of recycled aggregate concrete from various referenced studies.

Materials and Methodology
In this research, Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I was utilized as the primary binder. To ensure consistent quality throughout the experiments, the cement was stored in a dry environment. The aggregates used in this study included both natural and recycled materials. Natural coarse aggregates were composed of crushed granite with a maximum size of 20 mm, while

the fine aggregates were river sand passing through a 4.75 mm sieve, all conforming to ASTM C33 specifications.
The recycled aggregates were sourced from a local demolition site, processed by crushing concrete debris to the desired size, and sieved to achieve a grading similar to that of natural aggregates. The recycled fine aggregates were produced by further crushing and sieving the coarse recycled aggregates. Prior to their use, the recycled aggregates were washed to remove dust and adhered mortar. To improve workability without increasing water content, a superplasticizer complying with ASTM C494 Type F was employed. Additionally, an air-entraining admixture was used in some mixes to enhance freeze-thaw resistance. Potable water free from impurities was used for mixing and curing, maintaining a constant water-to-cement ratio (w/c) for all mixes.
Six concrete mixes with varying proportions of recycled aggregates were prepared. The replacement levels of natural aggregates with recycled aggregates were 0%, 25%, 50%, 75%, and 100% by volume. A control mix with 100% natural aggregates was also prepared. The mix design was based on ACI 211.1 guidelines. The concrete was mixed in a laboratory drum mixer. The dry aggregates (natural and recycled) were initially mixed for 2 minutes. Following this, cement was added, and the materials were mixed for another 2 minutes. Water containing the superplasticizer and air-entraining admixture was then gradually added, with mixing continuing for an additional 3 minutes.
Freshly mixed concrete was cast into standard molds, filling them in three layers, each compacted using a tamping rod. After 24 hours, the specimens were demolded and cured in a water tank at 23 ± 2°C until testing. Compressive strength tests, following ASTM C39, were performed on cylindrical specimens at 7, 28, and 90 days. The average strength from three specimens was reported. Tensile strength was assessed using ASTM C496 on cylindrical specimens, and flexural strength was measured on beam specimens according to ASTM C78, both at the same intervals.

Durability tests included permeability, assessed via the water penetration test per DIN 1048 on cubic specimens, with the penetration depth measured after 72 hours. Drying shrinkage was tested on prismatic specimens following ASTM C157, monitoring length change over 90 days. Freeze-thaw resistance was evaluated according to ASTM C666 Procedure A, subjecting specimens to 300 freeze-thaw cycles and measuring the relative dynamic modulus of elasticity.
The collected data were analyzed statistically to understand the impact of recycled aggregate content on concrete properties. Regression analysis was used to develop predictive models for compressive, tensile, and flexural strengths based on recycled aggregate proportions. Durability parameters were also correlated with mechanical properties to identify trends and relationships. This comprehensive methodology aims to assess the feasibility and performance of recycled aggregate concrete, contributing to sustainable construction practices.

Group Number	r/%	Effective Water–Cement Ratio	Material Consumption/kg·m^{-3}						Compressive Strength/N/mm^2
			Cement	Water	Natural Coarse Aggregate	Recycled Coarse Aggregate	Fine Aggregate	Additional Water	
NAC- I	0	0.527	370	195	1185	-	660	-	33.3
RAC-50- I	50	0.527	370	195	592.5	592.5	660	22.69	31.6
RAC-100- I	100	0.527	370	195	-	1185	660	45.38	32.4
NAC- II	0	0.40	500	200	1086	-	611	-	35.1
RAC-50- II	50	0.40	500	200	543	543	611	20.8	32.3
RAC-100- II	100	0.40	500	200	-	1086	611	41.6	30.9

Figure 3 The proportions of natural aggregates, recycled aggregates, cement, water, and any additives used in the concrete mixes [17]

Results and Discussion
Compressive Strength
The compressive strength results for concrete with varying proportions of recycled aggregates are summarized in Table 1. The data indicate a decrease in compressive strength as the proportion of recycled aggregates increases. The control mix with 100% natural aggregates exhibited the highest compressive strength at all tested ages (7, 28, and 90 days). However, concrete with 25% recycled aggregates showed only a slight reduction in strength, indicating that low levels of recycled aggregates can be used without significantly compromising compressive strength.

Table 1 Compressive strength of concrete mixes with varying recycled aggregate content at 7, 28, and 90 days.

Proportion of Recycled Aggregates	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
0% (Control)	32.5	41.2	45.3
25%	30.8	39.5	43.2
50%	28.6	36.8	40.7
75%	26.3	34.1	38.2
100%	24.1	31.6	35.5

As the proportion of recycled aggregates increased to 50% and above, the compressive strength saw more noticeable reductions. Concrete with 50% recycled aggregates had a compressive strength approximately 10-15% lower than the control mix at all ages. At 100% recycled aggregates, the reduction was more pronounced, with compressive strength approximately 25% lower than the control. This decrease is attributed to the weaker adhered mortar and potential impurities in the recycled aggregates. These findings align with previous research by Yang and Du (2011), who observed similar trends [9].

Tensile Strength

The splitting tensile strength results, presented in Table 2, show a tend similar to compressive strength, with tensile strength decreasing as recycled aggregate content increases. However, the relative reduction in tensile strength was less severe compared to compressive strength.

Table 2 Tensile strength of concrete mixes with varying recycled aggregate content at 7, 28, and 90 days.

Proportion of Recycled Aggregates	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
0% (Control)	3.1	3.8	4.1
25%	2.9	3.6	3.9
50%	2.7	3.3	3.7
75%	2.5	3.1	3.4
100%	2.3	2.9	3.2

Concrete with 25% recycled aggregates had a tensile strength within 5-7% of the control mix at all ages. At 50% recycled aggregates, the tensile strength was approximately 10-15% lower than the control, while concrete with 100% recycled aggregates showed a reduction of about 20%. These results are consistent with the findings of Xiao et al. (2012), who reported similar tensile strength behavior for recycled aggregate concrete [8].

Flexural Strength

The flexural strength results, shown in Table 3, also demonstrate a decrease with increasing recycled aggregate content, though the reductions were generally less pronounced than those observed for compressive and tensile strengths.

Table 3 Flexural strength of concrete with different recycled aggregate replacement levels.

Proportion of Recycled Aggregates	7 Days (MPa)	28 Days (MPa)	90 Days (MPa)
0% (Control)	4.2	5.4	5.9
25%	4.0	5.2	5.7
50%	3.8	5.0	5.4
75%	3.5	4.7	5.1
100%	3.3	4.4	4.8

Concrete with 25% recycled aggregates exhibited a flexural strength within 5% of the control mix at all ages. At 50% recycled aggregates, the flexural strength was about 7-10% lower than the control, and at 100% recycled aggregates, the reduction was approximately 15%. These results suggest that recycled aggregates can be used in concrete with relatively minor impacts on flexural strength, particularly at lower replacement levels.

Durability

Permeability

The permeability results, summarized in Table 4, indicated that recycled aggregate concrete generally exhibited higher water penetration depths compared to the control mix. This increase in permeability is attributed to the porous nature of the adhered mortar on recycled aggregates.

Table 4 Water penetration depth in concrete mixes with varying recycled aggregate content.

Proportion of Recycled Aggregates	Water Penetration Depth (mm)
0% (Control)	12
25%	15
50%	18
75%	21
100%	25

Concrete with 100% recycled aggregates had a water penetration depth approximately twice that of the control mix. However, at 25% and 50% recycled aggregates, the increase in permeability was more moderate, suggesting that partial replacement can still achieve acceptable durability.

Shrinkage

Drying shrinkage results, detailed in Table 5, showed an increase in length change with higher recycled aggregate content. This behavior is due to the higher absorption capacity and internal micro-cracks in recycled aggregates.

Table 5 Drying shrinkage of concrete mixes with different proportions of recycled aggregates over time.

Proportion of Recycled Aggregates	Length Change at 90 Days (%)
0% (Control)	0.045
25%	0.050
50%	0.056
75%	0.062
100%	0.068

Concrete with 25% recycled aggregates exhibited a slight increase in shrinkage compared to the control mix. At 100% recycled aggregates, the shrinkage was about 50% higher, indicating that higher proportions of recycled aggregates may require special attention to mitigate shrinkage effects.

Freeze-Thaw Resistance

Freeze-thaw resistance, as shown in Table 6, revealed that the relative dynamic modulus of elasticity decreased with increasing recycled aggregate content. However, concrete with up to 50% recycled aggregates-maintained freeze-thaw resistance within acceptable limits.

Table 6 Freeze-thaw resistance of concrete with varying recycled aggregate content.

Proportion of Recycled Aggregates	Relative Dynamic Modulus of Elasticity (%)
0% (Control)	97
25%	94
50%	90
75%	85
100%	80

Concrete with 100% recycled aggregates showed a more significant reduction in freeze-thaw resistance, but partial replacement levels of up to 50% still performed adequately. These findings align with those of Poon and Chan (2007), who reported similar observations [10].

The results of this research shed light on the intricate relationship between mechanical properties and durability when using recycled aggregates in concrete. The compressive strength tests revealed a consistent decrease with higher proportions of recycled aggregates, indicating that while concrete mixes with up to 25% recycled aggregates maintained comparable strength to conventional concrete, higher replacement levels led to more significant reductions. This aligns with findings from previous studies on the impact of recycled aggregates' adhered mortar content on compressive strength. Similarly, tensile and flexural strengths followed a similar trend of decreasing as recycled aggregate content increased, albeit with less severity compared to compressive strength. These results suggest that while the mechanical properties of recycled aggregate concrete are affected, partial replacement levels can still achieve acceptable performance, particularly in non-structural applications.

Durability assessments indicated that recycled aggregate concrete exhibited higher permeability and increased drying shrinkage compared to the control mix, attributed to the porous nature and micro-cracks in recycled aggregates. However, at lower replacement levels (up to 50%), the increase in permeability and shrinkage was moderate, suggesting that careful mix design and quality control measures can mitigate these effects. Freeze-thaw resistance tests showed that concrete with up to 50% recycled aggregates maintained adequate performance, while higher replacement levels showed a notable decrease in resistance. These findings underscore the importance of optimizing mix designs and incorporating supplementary materials to enhance the durability of recycled aggregate concrete in harsh environmental conditions.

Practically, the study supports the use of recycled aggregates as a sustainable alternative in concrete production, with recommendations for improving aggregate processing techniques and establishing standardized guidelines for quality control. Future research directions include exploring advanced treatments for recycled aggregates and conducting long-term field studies to validate laboratory findings and assess real-world performance. Overall, the study contributes valuable insights into balancing sustainability goals with concrete performance requirements in construction practices.

Conclusion

The utilization of recycled aggregates in concrete, focusing on their mechanical properties and long-term performance. The findings highlight several key points: first, lower replacement levels (up to 25%) of natural aggregates with recycled aggregates demonstrated minimal impact on compressive, tensile, and flexural strengths, suggesting feasibility for various construction applications without significant compromise in performance. However, higher replacement levels (50% and above) led to more pronounced reductions in strength, indicating the need for careful consideration and possibly additional measures to maintain structural integrity.

Secondly, the durability aspects revealed that recycled aggregate concrete generally exhibited higher permeability, increased drying shrinkage, and reduced freeze-thaw resistance compared to conventional concrete. Nevertheless, at moderate replacement levels (up to 50%), these durability concerns were manageable with proper mix design and quality control practices. This suggests that recycled aggregates can be effectively integrated into concrete production while meeting basic durability requirements, though careful attention is needed for more demanding applications and environments.

Practically, the study underscores the potential of recycled aggregates to contribute to sustainable construction practices by reducing the demand for natural resources and diverting construction waste from landfills. It advocates for optimized processing techniques and standardized guidelines to enhance the quality and consistency of recycled aggregates used in concrete.

Looking forward, future research should focus on refining aggregate processing methods, exploring innovative mix designs incorporating supplementary materials, and conducting long-term field studies to validate laboratory findings under real-world conditions. Such endeavors will further advance the adoption of recycled aggregate concrete as a viable and environmentally responsible solution in the construction industry. Ultimately, this study contributes valuable insights and recommendations to support the sustainable development and implementation of recycled aggregate concrete in construction practices worldwide.

Recommendations

Based on the comprehensive findings of this study on recycled aggregates in concrete, several recommendations emerge to enhance the practical application and sustainable integration of recycled materials in construction. Firstly, it is crucial to prioritize research and development efforts towards optimizing aggregate processing techniques. This includes exploring advanced methods such as mechanical crushing, thermal treatments, and chemical agents to improve the quality of recycled aggregates by reducing adhered mortar and enhancing particle grading. Secondly, there is a pressing need to refine mix designs specifically tailored for recycled aggregate concrete. Incorporating supplementary cementitious materials like fly ash or slag can help mitigate potential reductions in mechanical strengths and address increased permeability associated with recycled aggregates. Thirdly, rigorous quality control measures should be enforced throughout production processes to ensure consistency and reliability in the performance of recycled aggregate concrete. This involves stringent testing protocols for aggregate cleanliness, particle size distribution, and adherence to specified standards.

Conducting extensive field studies and long-term monitoring of structures built with recycled aggregate concrete is essential to validate laboratory findings and assess real-world performance. These studies should focus on evaluating structural integrity, durability, and maintenance requirements over extended periods, providing valuable insights for future applications. Standardization of guidelines and specifications for using recycled aggregates in concrete production is also critical to ensure uniformity in practices and facilitate broader acceptance within the construction industry. Moreover, education and awareness initiatives are necessary to inform stakeholders about the benefits and challenges associated with recycled aggregate concrete, promoting best practices and encouraging widespread adoption. Lastly, advocating for supportive policies and incentives at governmental and organizational levels can incentivize the adoption of sustainable construction practices and foster a circular economy approach in the construction sector. By implementing these recommendations collaboratively, stakeholders can effectively harness the environmental and economic benefits of recycled aggregates while advancing sustainable development goals in construction practices.

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