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REVIEW ARTICLE

Enhancing Off-Spec Limestone Aggregates with Polymer Treatment for Sustainable Infrastructure Construction – A Review

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ABSTRACT- The utilization of off-spec limestone aggregates in concrete production presents both challenges and opportunities for sustainable infrastructure development. These aggregates, abundant yet often failing to meet industry standards, remain underutilized despite their potential contribution to construction. The review assesses the characteristics of off-spec limestone aggregates, their implications on concrete performance, and explores polymer modification techniques to enhance their suitability for construction. Off-spec aggregates exhibit diverse physical and chemical attributes, varying from standard specifications, impacting their strength, durability, and composition. Polymer modification methods, including latex modification, silane coupling agents, epoxy and acrylic resin treatments, impregnation, physical modification, etc. offer avenues for improving aggregate properties, yet each technique presents distinct merits and demerits. The impact of polymer treatment manifests in changes to density, water absorption, and mechanical properties, as observed through SEM, FTIR, and BET analyses. Evaluating treated aggregates involves assessing their performance under diverse environmental conditions, including exposure to water, chloride solutions, and thermal stress cycles, revealing improvements in durability and bonding within concrete matrices. Implementing polymer-treated aggregates in construction projects proves feasible, offering enhanced mechanical properties, reduced water absorption, and potential environmental and economic benefits through reduced cement usage and waste generation. This review emphasizes the significance of complying with industry standards for size, strength, durability, and other physical and chemical properties to render off-spec aggregates suitable for concrete production. The amalgamation of various polymer modification techniques, as discussed comprehensively in the manuscript, not only ensures enhanced concrete performance but also contributes to the sustainability of infrastructure construction practices.

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INTRODUCTION

The utilization of off-spec limestone aggregates in concrete production presents both a challenge and an opportunity in the realm of sustainable infrastructure construction. Limestone, abundant in many regions, offers potential as a construction material. However, a significant portion of these resources especially

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under recycled conditions often fails to meet stringent industry specifications, limiting their utilization in concrete production [1].

Off-spec limestone aggregates, ranging from 5 mm to 10 mm, constitute a substantial portion of available natural aggregates in regions like Malaysia. These aggregates, though abundant, face limitations due to their inability to conform to the rigorous quality control standards set by the concrete industry [2]. As a result, these resources often remain underutilized or are completely disregarded, despite their potential contribution to the construction sector.

The challenges associated with off-spec aggregates revolve primarily around their failure to meet industry-specific requirements, including criteria related to size, strength, durability, and other physical and chemical properties. Conventional industry standards often necessitate specific characteristics in aggregates to ensure the structural integrity, longevity, and performance of concrete structures [3; 4]. The discrepancy between these standards and the properties of off-spec aggregates poses a significant obstacle to their widespread adoption.

In an era emphasizing sustainable development and infrastructure construction, the significance of aggregate quality cannot be overstated. Aggregates form the fundamental building blocks of concrete, directly influencing the performance, durability, and lifespan of infrastructure [5]. Sustainable construction practices demand the efficient utilization of available resources, including off-spec aggregates, to reduce waste and minimize environmental impact while ensuring the longevity and quality of constructed assets. This review focuses on the techniques and methods of polymer modification in off-spec aggregates to improve their quality and to utilize in infrastructure construction.

LITERATURE REVIEW

This section focuses on characteristics of off-spec limestone aggregates, different methods and techniques of polymer modification of the aggregates, effects of polymer treatment on the aggregates, evaluation of performance of treated aggregates, and the application of treated aggregates in the concrete industry.

Characteristics of Off-Spec Limestone Aggregates

Off-spec limestone aggregates are those that do not meet the standard specifications for use in construction. These aggregates, deviate from standard specifications in size, shape, gradation, strength, and durability, require treatment with polymers due to their inherent deficiencies (Table 1). The aggregates present variations in size, shape, and gradation, impacting concrete properties and workability, potentially leading to reduced strength and durability. Additionally, their susceptibility to weathering, and impurities affecting bond integrity with cement paste, and non-compliance with industry standards. All these challenges necessitate polymer treatments [6]. Polymers can address these issues by enhancing aggregates' cohesion, improving gradation uniformity, strengthening the bond with cement, and mitigating vulnerabilities to environmental factors. Treating off-spec limestone aggregates with polymers ensures improved concrete performance, increased durability, reduced permeability, enhanced workability, and minimizes the risk of structural failure in critical applications, aligning them closer to industry-specific standards for concrete production [4].

Islam and Mamun [7] recognized the limitations and deficiencies inherent in off-spec limestone aggregates, which may fail to meet the standard specifications required for road construction. In response to these challenges, the study proposes a solution involving the strategic combination of different types of aggregates. By blending various types of aggregates, the authors aim to improve the overall quality and performance of the road base and subbase layers. The abstract suggests that the proposed approach seeks to enhance the engineering properties of the construction materials, ultimately contributing to the effectiveness and durability of road infrastructure. This paper appears to offer valuable insights into mitigating the shortcomings associated with off-spec limestone aggregates in the context of road construction, providing a potential solution for optimizing road base and subbase materials.

Polymer Modification Techniques for Aggregate Enhancement

Modifying off-spec limestone aggregates with polymers is a method employed to enhance the qualities of recycled concrete aggregates, making them suitable for use in producing concrete. This process involves impregnating the aggregates with polymers to enhance their performance in terms of strength, durability, and other properties. Polymer modification techniques have emerged as a promising approach to enhance the properties of aggregates, the primary constituents of concrete. By modifying the surface properties of aggregates, there are some techniques that can significantly improve the adhesion between aggregates and cement paste, leading to enhanced concrete performance [5; 8].

Table 1. Characteristics of off-spec limestone aggregates and the reasons for polymer modification

Characteristic	Reason for polymer treatment	Reference
High water absorption	Treating polymers has the potential to enhance the durability and strength of concrete crafted from off-spec limestone aggregates	[10]
Poor thermal stability	Treatment with polymers can enhance the heat resistance of concrete produced using off-spec limestone aggregates in tropical climates	[10]
Higher porosity	Polymer treatment can reduce the porosity of off-spec limestone aggregates, improving their durability and performance in tropical climates	[11]
Low internal curing capacity	Using normal-density high-absorption limestone aggregate as an internal curing agent can enhance the effectiveness of concrete produced from off-spec limestone aggregates	[12]

Methods of polymer modification

Some of the techniques used for polymer modification of off-spec limestone aggregates include:

Impregnation: This method involves impregnating the recycled aggregates with polymers to improve their properties, such as compressive strength, water absorption, and durability [13]. The polymer-modified recycled aggregate concrete has shown marginal increases in compressive strength, while flexural strength is obtained by using other techniques [14].

Physical Modification: This technique involves removing small particle size aggregates and fine powder below 4.75 mm by sieving, and it leads to a notable decrease in water absorption and a rise in the average compressive strength of concrete [15].

Combination with other Technologies: Combining polymer strengthening with other technologies, like microbial-induced carbonization deposition, can enhance the overall strengthening effect of recycled aggregates in a more comprehensive manner [15].

Geopolymer-Based Artificial Aggregates: This approach involves using geopolymers to create artificial aggregates with desired properties, such as high Si and Al content, which can be applied in construction fields. Enhancing the characteristics of synthetic aggregates involves employing techniques like two-step palletization, alkali solution immersion, coating, and impregnation [16].

Autoclaving: This method utilizes substances such as fly ash and quarry tailings as the foundation for geopolymers, activating them through the inclusion of sodium hydroxide (NaOH) and sodium silicate

(Na_2SiO_3) The utilization of autoclaving results in the creation of artificial aggregates surpassing commercial ones, owing to their rounded configuration that improves concrete workability and enhances their absorption characteristics [16].

SBS Modified Asphalt Mixes: Incorporating Styrene-Butadiene-Styrene (SBS) modified asphalt mixes with different aggregates has demonstrated notable enhancements in strength attributes, resistance to rutting, and resilience to moisture. This method is applicable for enhancing the performance of limestone aggregates in asphalt mixes through modification [17].

Chemical Modification: Chemical modification methods involve treating recycled aggregates with specific chemicals or polymers to enhance their properties. Research progress in this area aims to explore the effectiveness of various chemical modification techniques for improving the quality of recycled concrete aggregates [15].

Bituminous Concrete Mixes: Research has examined how bituminous concrete mix performance is influenced by both aggregate type and polymer modification. The use of different aggregate types, such as limestone and riverbed aggregates, in combination with polymer modification, has shown improved results in terms of Marshall Stability and overall performance of the asphalt mixes [18].

Two-Stage Mixing Method: The two-stage mixing method, combined with cement paste encapsulating the aggregate technique, has been found to improve the physical and mechanical properties of RCA. This approach fills the voids and cracks with cement paste at the residual mortar surface, contributing to the enhancement of the RAC [19].

Aggregate Cleaning: Research has shown that the strength and quality of recycled concrete aggregates can be significantly influenced by the extent of aggregate cleaning, which depends on the roasting temperature of concrete rubble and the quantity of cement mortar extracted from the grain surface [19].

On the basis of the chemicals used to accomplish polymer modification of off-spec aggregates, the methods can be regarded as below-

Latex Modification: Latex modification involves coating aggregates with a latex polymer solution, typically styrene-butadiene rubber (SBR) or styrene-acrylic (SA). This creates a thin polymer film on the aggregate surface, enhancing its bond strength with cement paste [20].

Silane Coupling Agent Treatment: Silane coupling agents form covalent bonds with both the aggregate surface and cement paste, bridging the gap between the two materials. This results in a stronger interfacial bond and improved concrete performance [21; 22].

Epoxy Resin Modification: Epoxy resin modification involves coating aggregates with an epoxy resin, creating a durable and impermeable barrier on the aggregate surface. This enhances the aggregate's resistance to abrasion, chemical attack, and moisture penetration [23].

Acrylic Resin Modification: Acrylic resin modification involves coating aggregates with an acrylic resin, providing a flexible and water-resistant coating. This improves the aggregate's resistance to cracking and freeze-thaw cycles [24].

Polyurethane Resin Modification: Polyurethane resin modification involves coating aggregates with a polyurethane resin, creating a highly elastic and abrasion-resistant coating. This enhances the aggregate's resistance to impact and wear [24]. The resins synthesized comprise polymerized urethane, a resultant of the chemical interaction between an isocyanate and a hydroxyl group, depicted in Figure 1.

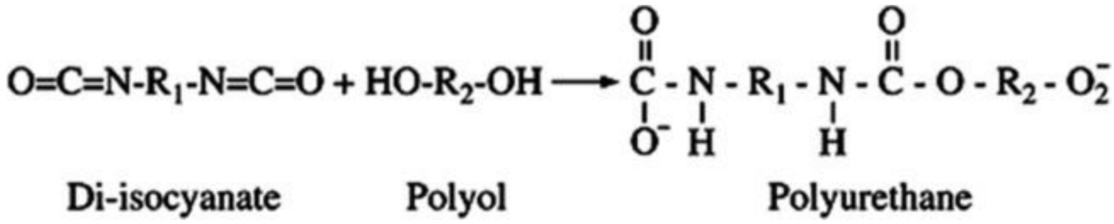

Figure 1. Chemical changes during polymerization of Urethane [25]

Techniques for Modifying Off-spec aggregates

The addition of polymers to the off-spec aggregates can be done using different techniques to have differential performance (Table 2).

Table 2. Techniques of polymer modification for aggregate enhancement

Technique	Description	Merits	Demerits	References
Dry Mixing Technique	Blend aggregates with resin in dry state	Simple, cost-effective, minimal equipment required	Uneven coating, inconsistent results	[26], [27]
Wet Mixing Technique	Mix aggregates and resin in wet state	Improved resin penetration, uniform coating	Additional mixing equipment, excess water content needed	[28]
Spray Application Technique	Apply resin onto aggregates using spraying equipment	Controlled application, efficient coverage	Needs specialized equipment, potential overspray	[22]
Chemical Bath Immersion Technique	Submerge aggregates in resin bath	Thorough resin impregnation, uniform treatment	Longer processing time, need for containment system	[29], [30]
Vacuum Impregnation Technique	Pull resin into aggregate pores using vacuum	Excellent penetration, enhanced bonding	Specialized equipment, complexity in achieving consistency	[31]
Heat-Cure Technique	Apply heat to cure resin-treated aggregates	Accelerates curing, improves resin adhesion	Additional heating equipment, temperature control issues	[32]

Detailed descriptions of the techniques have been narrated below:

i. Dry mixing technique

The technique involves blending aggregates with unsaturated polyester resin in a dry state, and allowing the resin to coat the aggregate surface. It is a simple and cost-effective method, easy to implement on-site, with minimal equipment required. However, uniform resin distribution might be challenging, potential uneven coating, variation in resin-to-aggregate ratio leading to inconsistent results.

ii. Wet mixing technique

It comprises of mixing aggregates and resin in a wet state to ensure better resin distribution and adhesion [33]. The main advantage of the technique is improved resin penetration into the aggregate pores, that creates uniform coating, and better control over resin-to-aggregate ratio [34]. It requires additional mixing equipment, longer processing time, potential issues with excess water content affecting concrete properties.

iii. Spray application technique

In this technique spraying equipment are utilized to apply unsaturated polyester resin onto the surface of aggregates. It provides a controlled and even application of resin, efficient coverage, suitable for large-scale production. But it requires specialized spraying equipment, potential overspray leading to material wastage, may necessitate proper ventilation due to resin fumes.

iv. Chemical bath immersion technique

In this procedure, the aggregates are immersed in a chemical solution containing unsaturated polyester resin to facilitate full saturation [29]. It ensures thorough resin impregnation, uniform treatment throughout aggregates, and excellent penetration [12]. However, it requires longer processing time, need for a containment system for the chemical bath, potential environmental and safety considerations due to chemical usage.

v. Vacuum impregnation technique

Involves creating a vacuum to pull unsaturated polyester resin into the pores of the aggregates, followed by pressure application to ensure penetration. It provides excellent resin penetration, enhanced bonding between resin and aggregates. But it requires specialized equipment for vacuum and pressure application, may create complexity in achieving consistent results, and needs higher operational costs [31].

vi. Heat-cure technique

Here heat is applied to cure the unsaturated polyester resin-treated aggregates to enhance bonding and setting the resin. The technique accelerates the curing process, and improves resin adhesion and strength [35]. It requires additional equipment for heating, and has potential issues with temperature control and uniform curing.

Effects of Polymer Treatment on Off-Spec Limestone Aggregates

The effects of polymer treatment on off-spec limestone aggregates are multifaceted, encompassing various physical, mechanical, and microstructural changes.

i. Changes in density and water absorption

Polymer treatment often leads to noticeable alterations in the density and water absorption characteristics of off-spec limestone aggregates. The incorporation of unsaturated polyester resin into the aggregates results in a modified surface and internal structure, which can affect their overall density. Typically, the treatment leads to a reduction in porosity due to resin infiltration, resulting in increased density. This reduction in porosity also contributes to decreased water absorption capacity, making the treated aggregates less susceptible to moisture ingress. Studies have shown that effective polymer treatment can significantly reduce water absorption in off-spec limestone aggregates, enhancing their durability and suitability for concrete applications [6].

ii. Mechanical property improvements

The application of polymer modification significantly enhances the mechanical properties of off-spec limestone aggregates, commonly evaluated through tests like Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV). ACV gauges the capacity of aggregates to withstand crushing under a gradually applied compressive load, whereas AIV assesses their ability to resist impact. Polymer treatment reinforces the aggregate structure, leading to enhanced strength and resistance to fragmentation. Studies have demonstrated that treated aggregates exhibit higher ACV and AIV values compared to untreated counterparts, indicating improved mechanical integrity and durability, which are crucial for their performance in concrete mixes [36].

iii. Microstructural changes

Studying alterations induced by polymer treatment through techniques like scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and Brunauer-Emmett-Teller (BET) analysis offers deeper insights into microstructural changes. SEM imaging often reveals a more uniform coating of aggregates with resin, indicating better resin distribution and penetration into the aggregate pores. FTIR analysis helps identify chemical changes and functional groups present after treatment, confirming the bonding between resin and aggregates. BET analysis reveals modifications in surface area and porosity, indicating improved bonding and decreased porosity due to resin infiltration [6].

Performance Evaluation of Treated Aggregates

Evaluating the performance of polymer-treated aggregates in infrastructure construction involves several steps. Initially, it's essential to evaluate the physical and mechanical traits of the processed aggregates, encompassing characteristics like particle size distribution, water absorption, and compressive strength [1]. These assessments involve employing conventional laboratory methods like conducting the sieve analysis, water absorption examination, and measuring compressive strength. Secondly, it's important to examine how the treated aggregates interact with other project materials, particularly their influence on concrete's workability and setting time [30]. This can be done using tests such as the slump test and the setting time test. Thirdly, the durability of the treated aggregates needs to be evaluated, such as their resistance to freeze-thaw cycles and chemical attack [37]. This can be done using tests such as the freeze-thaw test and the acid resistance test. There are several methods for evaluating the performance of polymer-treated off-spec aggregates. The objective of these techniques is to evaluate the efficacy of polymer treatments in enhancing both the physical and mechanical attributes of the aggregates (as depicted in Table 3).

Physical and Mechanical Testing: This encompasses performing evaluations to gauge the physical and mechanical attributes of the aggregates, including water absorption, density, workability, shrinkage, penetration, and mechanical strength through various tests [12; 15; 37].

Comprehensive Evaluation Methods: Developed comprehensive assessment approaches can be employed to evaluate the efficacy of various surface treatments, such as polymer impregnation, in enhancing the characteristics of recycled concrete aggregates [38].

Performance Testing: Performance evaluation involves testing the stability and durability of the aggregates when treated with polymers. This can include assessing the stability of the aggregates for use in roadways or other construction applications [39].

Water Absorption Test: This test quantifies the aggregate's water absorption capacity both pre and post polymer treatment. This assessment aids in gauging the treatment's efficacy in enhancing the water resistance of the aggregates [12].

Durability Testing: This entails assessing the enduring performance of the modified aggregates across diverse environmental conditions, including exposure to moisture, temperature fluctuations, and chemical agents. Durability testing helps to determine the stability and longevity of the polymer-treated aggregates [37].

Table 3. Methods of evaluation of performance of off-spec aggregates after polymer modification

Method/Technique	Short description	References
Mechanical testing	Mechanical testing is a common method for evaluating the performance of polymer-modified off-spec aggregates. This process entails assessing the mechanical characteristics of the altered aggregates, including measurements of compressive strength, tensile strength, and flexural strength. The merits of this method include its ability to provide quantitative data on the mechanical properties of the modified aggregates. Nevertheless, it might not offer a holistic depiction of how the aggregates would perform under real-world conditions.	[40], [41]
Durability testing	Durability testing is another method for evaluating the performance of polymer-modified off-spec aggregates. This approach involves exposing the modified aggregates to diverse environmental conditions, including freeze-thaw cycles, moisture-induced damage, and corrosion. The merits of this method include its ability to simulate real-world conditions and provide data on the long-term performance of the modified aggregates. However, it may not provide information on the mechanical properties of the aggregates.	[40],[41], [42]
Microscopic analysis	Microscopic analysis is a method for evaluating the microstructure of polymer-modified off-spec aggregates. This approach entails utilizing diverse imaging methodologies, including scanning electron microscopy (SEM) and X-ray diffraction (XRD), to examine the microstructural changes within the modified aggregates. The merits of this method include its ability to provide information on the distribution and orientation of the polymer within the aggregates. However, it may not provide information on the macroscopic properties of the aggregates.	[43], [44]
Field performance testing	Field performance testing is a method for evaluating the performance of polymer-modified off-spec aggregates in real-world conditions. This method involves subjecting the modified aggregates to actual traffic and environmental conditions and monitoring their performance over time. The merits of this method include its ability to provide data on the actual performance of the modified aggregates in real-world conditions. However, it may be time-consuming and expensive to conduct.	[40],[42], [44]
Rheological and Chemical Testing of Asphalt Binders	Rheological and chemical testing of asphalt binders is essential for evaluating the performance of polymer-modified bitumen. This method involves a thorough examination of asphalt binders utilizing rheological and chemical techniques to evaluate characteristics such as resistance to rutting, thermal cracking, fatigue damage, stripping, and susceptibility to temperature changes. The merits of this method include its ability to provide detailed insights into the performance characteristics of polymer-modified bitumen. However, it may require specialized equipment and expertise for testing and analysis.	[44], [45]
Impregnation testing	Testing for impregnation involves altering concrete spacers through polymer impregnation, for instance, using Methyl methacrylate. This approach seeks to evaluate the characteristics of concrete spacers subsequent to polymer impregnation. The advantage of utilizing this method is its efficacy in transforming the properties of concrete spacers through polymer impregnation. However, the specific testing standards and protocols for evaluating the performance of polymer-impregnated concrete spacers may need to be established.	[46], [47], [48]

X-ray Diffraction (XRD): This method involves examining the mineralogical composition of aggregates pre- and post-polymer treatment. XRD analysis aids in identifying alterations in crystal structure and the extent of polymer infiltration into the aggregates [38].

Microbial Carbonate Precipitation: This method entails leveraging microorganisms to induce calcium carbonate precipitation on the surface of recycled aggregates, thereby enhancing their characteristics and compatibility with cement-based materials. This method can be used to assess the effectiveness of polymer treatments in enhancing the performance of recycled aggregates [49].

Particle Packing Method (PPM): This approach is used to design the mix composition of recycled aggregate concrete, taking into account the particle packing density and the size distribution of the aggregates. PPM serves as a tool to assess how well polymer treatments enhance the workability and compressive strength of recycled concrete [50].

Scanning Electron Microscopy (SEM): SEM is employed to scrutinize the aggregates' microstructure pre and post polymer treatment, aiding in assessing both the extent of polymer penetration and alterations in the aggregates' surface morphology [38].

Fourier-Transform Infrared Spectroscopy (FTIR): FTIR enables the identification of surface functional groups on both treated aggregates and cement paste, offering insights into the chemical bonding mechanisms [47; 51].

Thermogravimetric Analysis (TGA): TGA can determine the weight loss of concrete samples as a function of temperature, providing insights into the decomposition of cementitious compounds and the potential impact of treated aggregates on these reactions [25].

Thermal Analysis: This method involves analyzing the thermal behavior of the aggregates before and after polymer treatment. Thermal analysis helps to determine the changes in the thermal stability and the degree of polymerization of the aggregates [37].

Rheological Testing: Rheological testing involves measuring the flow and deformation properties of the polymer-treated aggregates. This method helps to determine the effectiveness of the polymer treatment in improving the workability and flowability of the aggregates [12].

These tests provide valuable insights into the physical, chemical, and microstructural changes that occur in the aggregates after polymer treatment, helping to determine the effectiveness of the treatment in improving the properties of the aggregates.

Evaluating the performance of treated aggregates also involves exposure to various environmental conditions to assess their durability and examining their behavior in concrete applications. A few methods are described below:

i. Exposure to different environmental conditions

Durability testing involves subjecting the treated aggregates to diverse environmental conditions to simulate real-world scenarios. This includes immersing the aggregates in water, sodium chloride (NaCl) solution, and hydrochloric acid (HCl) solution to evaluate their resistance to moisture, chemical attacks, and corrosive agents. Exposure to these solutions over specific durations helps ascertain the aggregates' ability to withstand degradation, such as changes in mass, volume, or surface alterations, which can impact their long-term performance in concrete [52].

Immersion in Water: The primary concern with concrete structures is water exposure, which may result in the leaching of calcium hydroxide ($Ca(OH)_2$) from the cement paste, subsequently diminishing the concrete's alkalinity and rendering it vulnerable to rebar corrosion. Treated aggregates aim to fortify concrete against water infiltration by diminishing permeability and enhancing the adhesion between aggregates and cement paste [53].

Exposure to NaCl Solution: Chloride ions (Cl-) from salt exposure can accelerate the corrosion of steel reinforcement in concrete, leading to structural deterioration and potential failure. Treated aggregates can improve the concrete's resistance to chloride penetration by reducing the permeability of the concrete matrix and enhancing the corrosion protection of the reinforcement [54].

Exposure to HCl Solution: Acidic environments, such as those encountered in industrial or wastewater applications, can attack the cement paste and degrade the concrete's integrity. Treated aggregates can enhance the concrete's resistance to acid attack by modifying the surface properties of aggregates and improving the bond between aggregates and cement paste, reducing the penetration of acidic solutions [53].

Thermal Stress Cycles: Thermal stress cycles, caused by variations in temperature, can induce cracking and deterioration in concrete structures. Treated aggregates can improve the concrete's resistance to thermal stress by reducing its thermal expansion coefficient and enhancing the bond between aggregates and cement paste, minimizing cracking and maintaining structural integrity.

ii. Chemical reactions and bonding in concrete

The use of treated aggregates in concrete mixtures allows for the assessment of chemical interactions and bonding between the aggregates and the cementitious matrix. Incorporating treated aggregates into concrete specimens facilitates the observation of chemical reactions between the aggregates and cement paste during hydration. Techniques such as petrographic analysis and chemical analysis of concrete samples containing treated aggregates help evaluate the bonding, interfacial transition zone, and any potential adverse effects on the concrete's microstructure. This assessment aids in determining the overall performance and durability of concrete structures when utilizing treated aggregates. Various techniques can be employed to evaluate these interactions, including [47; 52].

Therefore, a comprehensive evaluation of the performance of treated aggregates requires a combination of exposure testing under various environmental conditions and detailed analysis of the chemical reactions and bonding mechanisms at the aggregate-cement paste interface. By understanding the impact of treatment on the durability and microstructure of concrete, engineers can make informed decisions about the selection and utilization of treated aggregates for specific applications.

Discussion on Performance Evaluation

The assessment of polymer-treated aggregates involves a multifaceted approach. Initial evaluations encompass physical and mechanical traits through conventional methods like sieve analysis, water absorption tests, and compressive strength measurements. Interactions with project materials, effects on concrete workability and setting time, and assessments of durability against freeze-thaw cycles and chemical attacks are crucial. Various techniques such as XRD, microbial carbonate precipitation, SEM, FTIR, TGA, and rheological testing provide insights into microstructural changes and chemical bonding. Exposure testing to environmental conditions like water, NaCl, HCl, and thermal stress cycles gauges durability. Assessing chemical reactions and bonding in concrete involves techniques like petrographic and chemical analysis. This comprehensive evaluation informs the selection and utilization of treated aggregates for optimal performance in specific applications.

Application of Treated Aggregates in Concrete Industry

Polymer-treated off-spec limestone aggregates are a type of enhanced aggregates that have been treated with polymer to improve their properties. Employing these aggregates within the concrete sector offers numerous benefits. Initially, these methods aim to enhance concrete's mechanical characteristics, including compressive strength, flexural strength, and toughness. Additionally, they can lower concrete's water absorption, enhancing its durability and fortifying it against freeze-thaw cycles. Thirdly, they can reduce the amount of cement required in concrete, which can lead to cost savings and environmental benefits [6; 55].

The feasibility and scalability of implementing polymer-treated aggregates in construction projects depend on several factors, such as the availability of raw materials, the cost of production, and the compatibility of the aggregates with other materials used in the project. Nevertheless, multiple research works have indicated the feasibility and scalability of employing polymer-treated aggregates for extensive application in significant construction endeavors [6; 36].

The economic and environmental implications of utilizing polymer-treated aggregates are also significant. The use of these aggregates can lead to cost savings due to the reduced amount of cement required in concrete. Furthermore, employing these aggregates can diminish the carbon footprint of concrete manufacturing through a reduction in necessary cement volume. Moreover, employing these aggregates can decrease the concrete production's waste output, potentially resulting in environmental advantage [6].

Suggestion for Future Studies

Future studies in this field should explore advanced polymer modification techniques and their impact on off-spec aggregates. Investigating novel polymers and their combinations could enhance aggregate properties. Additionally, research should focus on the long-term performance and sustainability of treated aggregates in real-world applications. Further studies can delve into the optimization of polymer dosages for different aggregate types and sizes, considering economic and environmental factors. Exploring the effects of polymer-treated aggregates on the overall life cycle of concrete structures and assessing their environmental impact would contribute valuable insights. Furthermore, research could address the scalability and practical implementation of polymer-treated aggregates in large-scale construction projects.

CONCLUSION

The review underscores the complexities surrounding off-spec limestone aggregates in concrete production and their potential for sustainable infrastructure. Off-spec aggregates, deviating from standard specifications, pose challenges in strength, gradation, and durability. However, polymer modification emerges as a promising avenue, offering techniques to enhance these aggregates for construction purposes. The impact of polymer treatment reflects in altered density, water absorption, and improved mechanical properties, validated through comprehensive analyses. Evaluating their performance under diverse environmental conditions demonstrates enhanced durability and bonding in concrete applications. Despite challenges, the feasibility of implementing polymer-treated aggregates in construction projects shows promise, presenting economic and environmental advantages through reduced cement usage and waste generation. This study highlights the transformative potential of polymer modification in repurposing off-spec aggregates, bridging the gap between industry standards and sustainable infrastructure construction.

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