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Innovation in the Use of Rigid Pavement Waste in Recycled Concrete: Challenges and Solutions to Improve Mechanical Performance

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ABSTRACT

The use of rigid pavement waste as recycled aggregate in concrete has become a focus of research in an effort to improve sustainability in the construction industry. This article discusses the main challenges in using rigid pavement waste as recycled aggregate, especially related to the mechanical strength of concrete, such as compressive and flexural strength. In addition, this article also explores various innovations in concrete mix design that can overcome the mechanical performance weaknesses of recycled concrete. Some of the solutions discussed include the use of reinforcing fibers, alternative binders, and more efficient production technologies. The research shows that these innovations can significantly improve the performance of recycled concrete with rigid pavement waste aggregate, making it a viable option to support more environmentally friendly infrastructure development.

Keywords: recycled concrete; rigid pavement waste; mechanical strength; concrete mix innovation; reinforcing fibers; alternative binders.

INTRODUCTION

The construction industry has long been recognized as one of the largest contributors to global environmental problems, including construction waste and carbon emissions. The use of large amounts of concrete in infrastructure projects increases pressure on natural resources, especially the coarse and fine aggregates used in concrete mixes. Natural aggregates, which are generally obtained from mining, are becoming increasingly scarce, and the process of exploiting these resources often causes serious environmental damage. To reduce these negative impacts, various studies have been conducted to explore the use of rigid pavement waste as recycled aggregate in concrete [1].

Although the use of rigid pavement waste as recycled aggregate offers a more sustainable solution, there are significant challenges that must be overcome, especially regarding the mechanical performance of concrete. The use of recycled aggregate often results in a decrease in the flexural strength and durability of concrete, especially if the proportion of recycled aggregate used is quite high. To overcome this problem, innovations in concrete mix design need to be continuously developed to improve the mechanical strength of recycled concrete, so that it can be widely used in various infrastructure projects [2].

This article discusses the main challenges in using rigid pavement waste as recycled aggregate in concrete and explores innovative solutions that can improve the mechanical performance of recycled concrete. The focus of this article is on the use of reinforcing fibers and alternative binders that can improve compressive and flexural strength, as well as more efficient production technologies to ensure the quality of recycled aggregate [3].

The construction industry plays a vital role in the development of infrastructure around the world. However, along with its vital role, this industry is also one of the sectors that generates significant solid waste and carbon emissions. According to various studies, the construction industry contributes 30-40% of the total global solid waste and produces around 10-20% of the total carbon dioxide (CO2) emissions produced by humans each year. One type of waste produced is waste from concrete road paving, or what is known as rigid pavement waste. This waste is often generated from road repair and maintenance projects, the volume of which continues to increase along with the need for better and more durable infrastructure [4].

Rigid pavement waste is generated when concrete roads experience wear, damage, or when increased traffic capacity requires repair and replacement of roads. This repair process usually involves demolition of old concrete, which then produces large amounts of rigid pavement waste. Without proper management, this waste ends up in landfills and has the potential to pollute the environment. In addition, the disposal of rigid pavement waste to landfills requires large areas of land, exacerbating land-limited problems in many countries.

With the increasing awareness of the importance of sustainability in various industrial sectors, including construction, recycling of building materials has been proposed as one of the solutions to reduce the environmental footprint of this industry. Rigid pavement waste is considered as a potential material to be recycled and reused as aggregate in concrete mixes. The use of this waste as recycled aggregate can not only reduce the volume of waste generated, but also help reduce the use of increasingly limited natural aggregates.

Natural aggregates, such as gravel and sand, make up the majority of the materials used in concrete production. However, over-exploitation of these aggregate resources has led to serious environmental problems, including land degradation, habitat loss, and increased carbon emissions from the mining and transportation of aggregates. Therefore, the use of recycled aggregates from rigid pavement waste offers a more environmentally friendly alternative, especially in the context of sustainable development.

Potential of Rigid Pavement Waste as Recycled Aggregate

Rigid pavement waste has characteristics that make it suitable for reuse as aggregate in concrete. Rigid pavement concrete used in road construction usually has high compressive strength and resistance to heavy traffic loads. When this concrete is crushed, the resulting material still retains most of the mechanical properties of the original concrete, such as compressive strength and abrasion resistance. Therefore, rigid pavement waste can be used as coarse aggregate in new concrete, either partially or completely replacing natural aggregate.

The use of rigid pavement waste as recycled aggregate in concrete has also been shown to increase concrete density and improve the bond between cement paste and aggregate. Research shows that concrete mixtures with a certain proportion of rigid pavement waste can produce compressive strength equivalent to concrete using natural aggregates, especially in the early drying phase. This shows that recycled aggregates from rigid pavement waste can provide good mechanical performance in structural applications, such as road pavements, buildings, and other infrastructure.

In addition to compressive strength, concrete with recycled aggregates must also have good flexural strength, especially in applications that require resistance to dynamic loads, such as highways and bridges. However, one of the main challenges in using rigid pavement waste as recycled aggregate is the decrease in flexural strength, especially when the proportion of waste used is quite high (above 60%). This is due to the higher porosity of recycled aggregates compared to natural aggregates, which reduces the flexibility of concrete and makes it more susceptible to cracking. To overcome this problem, various innovations have been proposed, including the use of reinforcing materials such as polymer fibers or steel fibers to increase the flexural strength of recycled concrete.

Figure 1. Concrete Waste

Environmental Impact of Using Recycled Aggregates

One of the main advantages of using rigid pavement waste as recycled aggregate in concrete is the reduction of environmental impact. From a sustainability perspective, recycled concrete offers several significant environmental benefits, ranging from reduced construction waste to reduced carbon emissions. The use of recycled aggregate in concrete can reduce dependence on virgin aggregate, which requires energy-intensive mining and processing processes. This process produces significant carbon emissions, mainly from the use of fossil fuels in mining and transporting the aggregate.

On the other hand, the use of recycled aggregates can substantially reduce carbon emissions, especially if the recycled material is sourced from a location close to the construction project. Research shows that the use of recycled aggregates from rigid pavement waste in a proportion of 30-60% concrete mixes can reduce carbon emissions by 20-30%, depending on the production process and transportation of the material [2]. This makes recycled concrete a more environmentally friendly alternative to conventional concrete.

In addition, the use of rigid pavement waste in recycled concrete can also reduce construction waste that is disposed of in landfills. Given the high volume of rigid pavement waste generated from road repair projects, diverting this waste to the recycling process can significantly reduce the burden on landfills. This not only helps save increasingly limited land, but also reduces the potential for environmental pollution caused by the disposal of concrete waste.

Challenges in Using Rigid Pavement Waste as Recycled Aggregate

While the use of rigid pavement waste in recycled concrete offers several advantages, there are a number of technical challenges that need to be overcome to ensure that this recycled material can be widely used in the construction industry. One of the main challenges is the consistency of the quality of recycled aggregates. Rigid pavement waste generated from different projects can have varying qualities, depending on the type of concrete used, the age of the material, and the crushing method applied. Therefore, it is essential to conduct a comprehensive quality evaluation of recycled aggregates before they are used in concrete mixes.

Recycled aggregates generally have higher porosity and greater water absorption than virgin aggregates, which can affect the mechanical performance of concrete, especially in terms of compressive strength and resistance to freeze-thaw cycles. Concrete with recycled aggregates may require admixtures, such as superplasticizers or alternative binders, to improve performance and durability under various environmental conditions.

In addition, the long-term durability of recycled concrete is also a significant challenge. The use of rigid pavement waste in concrete must be tested under actual field conditions to assess its resistance to traffic loads, temperature changes, and other environmental factors. Large-scale field tests are needed to evaluate the long-term performance of recycled concrete in applications such as road and bridge pavements. These tests are important to ensure that recycled concrete not only meets the mechanical strength standards in the initial phase, but also has good durability in the long term.

Research shows that the use of recycled aggregates from rigid pavement waste in a fairly high proportion (more than 60%) often causes a decrease in the compressive and flexural strength of concrete. This decrease is caused by several factors, including the higher porosity of recycled aggregates and greater water absorption compared to natural aggregates. This higher porosity reduces the bond strength between the cement paste and aggregates, which ultimately affects the overall mechanical performance of the concrete [5].

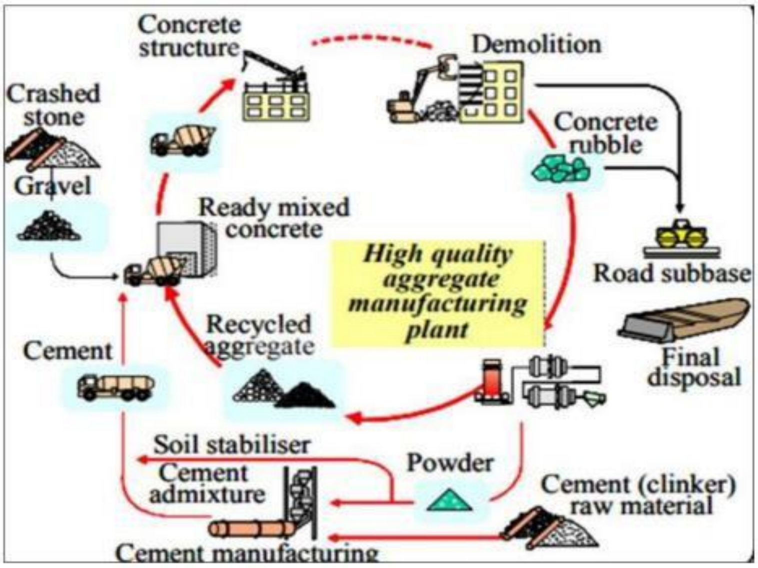

Figure 2. Schematic flow of concrete recycling system

Innovation in Recycled Concrete Mix Design

To overcome these challenges, several innovations in concrete mix design have been proposed and tested in various studies. The following are some innovative solutions that can improve the mechanical performance of recycled concrete with waste aggregates of rigid pavement.

Use Fiber Amplifier

One of the most common solutions used to increase the flexural strength of recycled concrete is the use of reinforcing fibers, such as steel fibers or polymer fibers. Research shows that the addition of fibers can significantly increase the flexural strength of concrete, because these fibers help bind recycled aggregates and strengthen the bond between cement paste and aggregates. Reinforcing fiber also helps prevent cracks from occurring due to dynamic loads or freeze-thaw cycles, thereby increasing the long-term durability of concrete [1]. A study conducted by [5], the addition of steel fibers in recycled concrete with a proportion of 50% recycled aggregates from rigid pavement waste increased the flexural strength by up to 20% compared to concrete without fibers. These fibers work by distributing the stress received by the concrete, thereby preventing significant cracking. Thus, the addition of reinforcing fibers is an effective solution to improve the mechanical performance of recycled concrete, especially in road pavement applications.

Use Material Binder Alternative

In addition to reinforcing fibers, another innovation that can improve the performance of recycled concrete is the use of alternative binders, such as geopolymer cement or fly ash [6]. Geopolymer

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cement, made from pozzolanic materials such as fly ash, offers advantages in terms of reducing carbon emissions, because its production process produces much lower emissions compared to conventional Portland cement. The use of geopolymer cement in recycled concrete has been shown to increase the compressive strength and durability of concrete, as well as reduce the environmental impact of concrete production [2]. A study conducted by [7] showed that the use of fly ash as a binder in recycled concrete increased the compressive strength by up to 15%, because fly ash helps improve the bond between recycled aggregate and cement paste. In addition, fly ash also reduces the porosity of the aggregate, thereby increasing the resistance of concrete to water penetration and freeze-thaw cycles.

More Efficient Production Technology

In addition to innovations in concrete mix design, the development of more efficient crushing technology is also an important factor in improving the quality of recycled aggregates. The crushing process of old concrete must be carried out in such a way that the resulting aggregate has a quality close to that of natural aggregates. Effective crushing will help remove old mortar attached to the aggregate, thereby reducing porosity and improving the mechanical performance of recycled concrete. Technologies such as jaw crushers and impact crushers have been widely used in the concrete recycling process, but these technologies still need to be further developed to improve energy efficiency and reduce fuel consumption in the crushing process. More sophisticated technologies can produce higher quality recycled aggregates, which will ultimately improve the performance of recycled concrete in various structural applications [1].

Research on concrete mixtures utilizing rigid pavement waste as recycled aggregates begins with analyzing the raw materials. In this process, the characteristics of rigid pavement waste such as composition, particle size, and other physical properties must be thoroughly identified. This is important to ensure that the recycled material can meet the quality standards of concrete in structural applications. In addition, it is necessary to evaluate additional materials such as superplasticizers, alternative binders, or reinforcing fibers to improve the performance of recycled concrete, considering that recycled materials may have different physical and mechanical properties compared to natural materials [1].

Once the characteristics of the raw materials are understood, the next step is to develop a concrete mix formula that considers the ratio and proportion between traditional raw materials and rigid pavement waste. The mixing process is followed by laboratory tests to test the compressive strength, tensile strength, resistance to deformation, and density of the concrete. Other mechanical tests, such as tensile, flexural, and compression tests, are carried out to assess the overall performance of the concrete [5]. Numerical simulations or structural tests are also needed to test the performance of concrete in real applications, such as road and bridge pavements, with the aim of producing concrete that has optimal structural strength, including resistance to dynamic loads as well as shear and fatigue strength [8], [9].

Environmental impact evaluation of the use of rigid pavement waste is also important. Reducing carbon emissions and reducing construction waste are the main focuses in assessing the sustainability of recycled concrete. This evaluation is carried out through a life cycle analysis (LCA), which allows comparison between recycled concrete and conventional concrete in terms of sustainability and cost efficiency [2]. In addition, the development of appropriate mixing methods and production technologies is essential to ensure the quality and consistency of recycled concrete and to increase energy efficiency in its production process [1].

Concrete that uses rigid pavement waste as recycled aggregate has several important characteristics that affect its performance. Compressive strength is one of the main properties that determines the ability of concrete to withstand compressive loads. This strength can be affected by the composition of the mixture, aggregate size [10], and curing conditions. Research shows that the use of recycled aggregates can affect the compressive strength of concrete. For example, the results of research at the Muhammadiyah University of Palembang showed that concrete with used aggregates has good compressive strength, with values reaching 225.956 kg/cm² to 243.389 kg/cm² [11].

In addition, concrete tends to have lower tensile strength compared to compressive strength, so it is often necessary to add reinforcing materials, such as fibers, to increase its tensile strength. In this case, the use of recycled aggregates from rigid pavement waste may require additional reinforcing materials to improve tensile performance, especially for applications that require resistance to high tensile loads [12]. Meanwhile, the elastic modulus of recycled concrete is generally lower than that of concrete using natural aggregates [13]. This is due to the nature of recycled aggregates which are more fragile or have higher water absorption, which can affect the bond between particles in concrete [7].

Resistance to deformation is also an important factor in recycled concrete. This concrete must be able to withstand deformation due to temperature variations or dynamic loads. The use of rigid pavement waste as recycled aggregate can help improve the concrete's resistance to deformation, especially if the proportion of coarse and fine aggregates is well adjusted. In addition, good concrete must have resistance to water penetration to avoid damage caused by freeze-thaw cycles, corrosion of reinforcing steel, or chemical attacks. Recycled concrete with rigid pavement waste aggregate may have higher porosity, requiring capillarity or permeability testing to ensure water resistance.

Concrete used in environments with repeated freeze-thaw cycles must be able to withstand significant damage. Therefore, it is important to test recycled concrete from rigid pavement waste to ensure its resistance to extreme temperature changes, especially for applications in road pavements [14]. The setting time of concrete can also be different in recycled concrete. The use of certain chemicals can help control the optimal setting time to achieve the desired compressive strength.

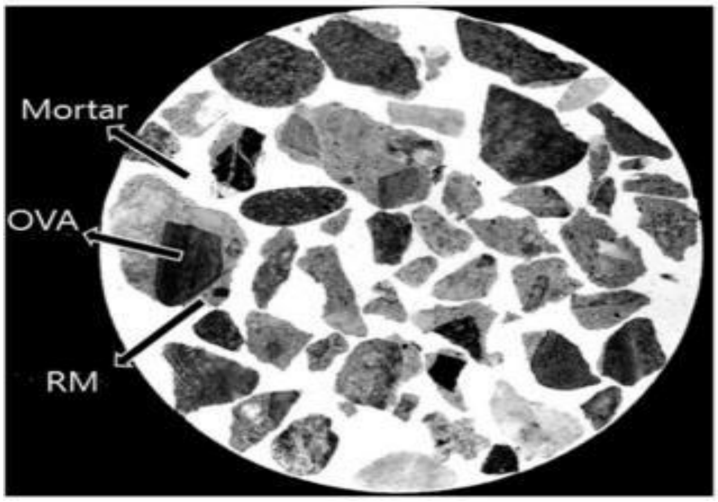

Figure 3. Polished concrete test specimen mixed with white cement and coarse RCA only

Aesthetically, concrete using rigid pavement waste may have a different color or texture compared to conventional concrete. Although not a primary mechanical property, this factor is important to consider in architectural applications that require a certain visual appearance [15].

Considering these characteristics, recycled concrete using rigid pavement waste aggregates has great potential in supporting sustainable development, especially in road pavement projects. However, to ensure that this recycled concrete complies with applicable construction standards, the mixture proportion and use of appropriate additives must be optimized [16].

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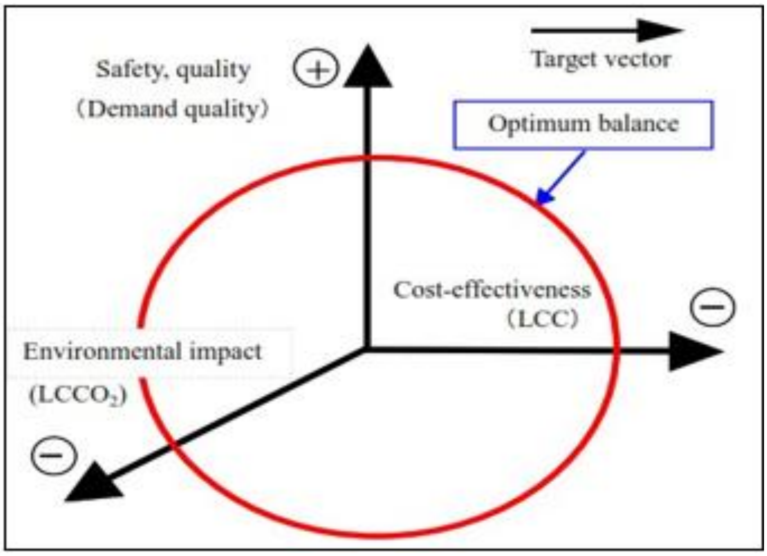

Figure 4. Recycling Assessment

In the face of global environmental challenges, the construction industry must adapt to more sustainable practices. The use of rigid pavement waste as recycled aggregate in concrete is one step that can be taken to reduce the environmental impact of the industry. Although there are technical challenges in terms of material quality and long-term performance, innovations in concrete mix design and recycling technologies can help address these issues. Thus, recycled concrete with rigid pavement waste can be an effective solution to support the development of more environmentally friendly infrastructure, while reducing the environmental footprint of the construction industry.

The use of rigid pavement waste as recycled aggregate in concrete has been the subject of extensive research in recent decades, along with the increasing global awareness of sustainability and efforts to reduce construction waste. Concrete is one of the most widely used construction materials, consisting of a mixture of cement, water, and aggregates (both coarse and fine). Natural aggregates, which are generally derived from gravel and sand mining, are the main components in concrete, but overexploitation of this resource has resulted in significant environmental impacts, including land degradation and carbon emissions. Therefore, the use of construction waste such as rigid pavement waste as recycled aggregate is a viable alternative to reduce these negative impacts [1].

Use of Recycled Aggregates in Concrete

The use of rigid pavement waste as recycled aggregate not only reduces the need for natural aggregates, but also reduces construction waste that must be disposed of in landfills. The process of crushing rigid pavement produces coarse aggregate that still has good mechanical properties, such as compressive strength and resistance to dynamic loads, which allows its use in new concrete mixes. However, there are several technical challenges that must be overcome to ensure optimal performance of this recycled concrete, especially in terms of mechanical properties and long-term durability [12].

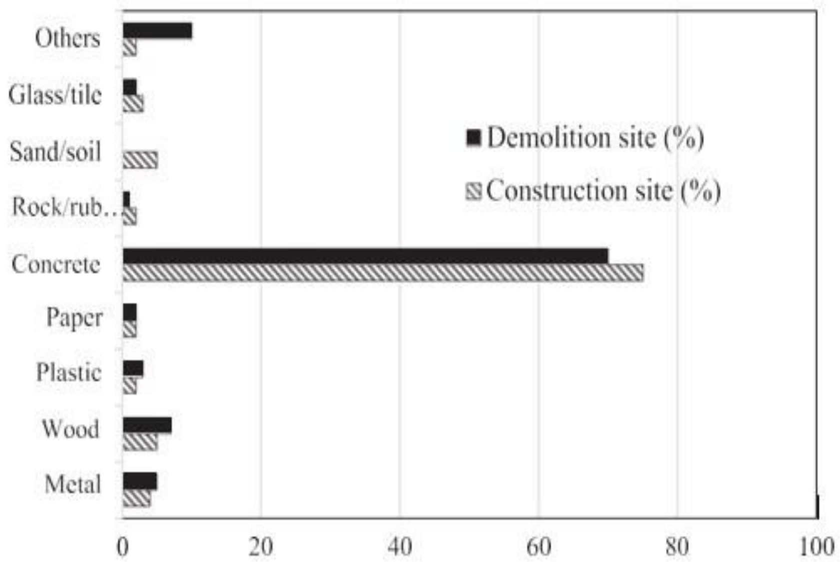

Figure 5. Typical composition of construction and demolition waste

Various studies have been conducted to evaluate the performance of concrete using recycled aggregates from rigid pavement waste. These studies usually include testing the mechanical strength of concrete, such as compressive strength and flexural strength, as well as evaluating the environmental impact of using the waste. Most studies show that concrete with a certain proportion of rigid pavement waste has comparable performance to concrete using natural aggregates, especially in terms of compressive strength. However, some studies also show a decrease in flexural strength in concrete with a high proportion of recycled aggregates, mainly due to the higher porosity of recycled aggregates compared to natural aggregates [2].

Compressive and Flexural Strength

Compressive strength is one of the most important parameters in assessing the mechanical performance of concrete. It describes the ability of concrete to withstand a given compressive load without experiencing structural damage. Research conducted by [1] showed that the use of recycled aggregates from rigid pavement waste in concrete mixtures can produce quite good compressive strength, especially in the early hardening phase. At a proportion of 30-60%, recycled concrete with rigid pavement aggregates showed an increase in compressive strength, mainly due to increased concrete density and improved bonding between cement paste and aggregate.

However, the compressive strength of concrete with a proportion of 100% recycled aggregate from rigid pavement waste tends to decrease. This is due to the nature of recycled aggregates which have higher porosity and greater water absorption compared to natural aggregates. This higher water absorption can reduce the amount of water available for the cement hydration process, which ultimately affects the compressive strength of concrete. Therefore, concrete with a high proportion of recycled aggregates may require modifications in the mixed design, such as the addition of binders or additives to improve its mechanical performance [5].

In addition to compressive strength, flexural strength is also an important parameter in assessing the performance of concrete, especially in applications that require resistance to flexural or dynamic loads, such as highways and bridges. Concrete naturally has low tensile strength, and this is one of its main weaknesses in structural applications. The use of rigid pavement waste as recycled aggregate can affect the flexural strength of concrete, especially if the proportion of recycled aggregate used is quite high.

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Figure 6. Compression and Flexural Test Objects

Research conducted by [12] shows that concrete with a proportion of 30-60% recycled aggregate from rigid pavement waste still has quite good flexural strength. However, at a proportion of 100%, the flexural strength of the concrete decreased significantly. This is due to the nature of recycled aggregates which are more fragile and tend to have higher water absorption, which reduces the ability of concrete to withstand flexural loads. To overcome this decline, several studies suggest the use of reinforcing materials such as polymer fibers or steel fibers to increase the flexural strength of recycled concrete [1].

Modulus of Elasticity

The modulus of elasticity is a measure of the stiffness of concrete, which describes how quickly the concrete will return to its original shape after being loaded. Concrete with recycled aggregates tends to have a lower modulus of elasticity compared to concrete using natural aggregates. This is due to the nature of recycled aggregates which are more brittle and have a less strong bond with the cement paste. Therefore, concrete with recycled aggregates may be more susceptible to deformation due to dynamic loads or temperature changes [7].

Research shows that although the compressive strength of concrete with recycled aggregates can be comparable to conventional concrete, the lower modulus of elasticity can affect the long-term performance of the concrete, especially in applications requiring high stiffness. To overcome this problem, modifications are needed in the concrete mix design, such as the addition of alternative binders or superplasticizers to improve the bond between the recycled aggregate and the cement paste.

Resistance to Freeze-Defreeze Cycles

One of the biggest challenges in using recycled concrete is its resistance to freeze-thaw cycles, especially in extreme climate conditions. Concrete used in environments with drastic temperature changes must be able to withstand repeated freeze-thaw cycles without experiencing structural damage. Concrete with recycled aggregate from rigid pavement waste may be more susceptible to freeze-thaw damage due to the higher porosity of the aggregate and greater water absorption.

Research conducted by [14] showed that recycled concrete with rigid pavement aggregates must be thoroughly tested to ensure its resistance to freeze-defrost cycles. Capillarity or permeability tests are also needed to assess the resistance of concrete to water penetration, which can cause damage to the concrete when the absorbed water freezes and causes expansion.

Effect of Adding Strengthening Materials

To overcome the weaknesses in flexural strength and elastic modulus, various studies have explored the use of reinforcing materials in recycled concrete. One of the most common approaches is the use of polymer fibers or steel fibers to increase the tensile and flexural strength of concrete. The addition of these fibers helps to increase the flexibility of concrete and reduces its susceptibility to cracking under dynamic loads.

Research conducted by [5] shows that the addition of steel fibers in recycled concrete with rigid pavement aggregates can increase flexural strength by 15-20%, depending on the proportion of fibers used. In addition, the use of alternative binders such as fly ash or geopolymer cement has also been shown to help improve the bond between recycled aggregates and cement paste, which ultimately increases the compressive and flexural strength of concrete.

Environmental Impact of Using Recycled Aggregates

The use of rigid pavement waste as recycled aggregates not only provides benefits in terms of mechanical performance, but also from an environmental perspective. The use of recycled aggregates can reduce carbon emissions resulting from the mining and processing of natural aggregates. In addition, the use of recycled aggregates can reduce the volume of construction waste that must be disposed of in landfills, which helps save land and reduce the potential for environmental pollution.

Life cycle analysis (LCA) conducted by [2] shows that the use of recycled aggregates in proportions of 30-60% can reduce carbon emissions by 20-30%, depending on the production process and transportation of the material. This makes recycled concrete with rigid pavement waste a more environmentally friendly alternative compared to conventional concrete. In addition, the development of more efficient recycled aggregate crushing and recovery technologies can also help reduce the carbon footprint of the recycling process itself.

RESULTS AND DISCUSSION

The use of rigid pavement waste as recycled aggregate in concrete offers several advantages from a sustainability perspective, including reduction of construction waste and reduction of exploitation of natural aggregates. However, technical challenges related to the mechanical performance and durability of recycled concrete require special attention to ensure its widespread adoption in the construction industry. This section will discuss these challenges in more depth, as well as proposed solutions to overcome the shortcomings inherent in recycled concrete using rigid pavement waste aggregate.

Recycled Aggregate Quality

One of the main challenges in using rigid pavement waste as recycled aggregate is the consistency of the quality of the material produced. The quality of recycled aggregate is highly dependent on the source and crushing method used. Concrete used in road projects can have different compositions depending on factors such as the type of initial concrete, application method, and curing conditions during its service life. Older concrete may have undergone chemical or physical degradation that results in reduced material quality when crushed into recycled aggregate. In addition, the crushing method used to process rigid pavement waste can affect the size and shape of the recycled aggregate, which ultimately affects its mechanical performance [5].

To address this issue, it is important to have clear standards regarding the concrete recycling process, including crushing methods and evaluation of the quality of the resulting material. Further research is needed to develop crushing technologies that can minimize aggregate degradation and maintain mechanical properties close to those of natural aggregates. One technology that can be explored is the use of more precise impact crushers, which can better separate old mortar from aggregates, resulting in higher quality aggregates [2].

In addition, rigorous evaluation steps are required to ensure that recycled aggregates meet the quality standards required for structural applications. Laboratory tests to evaluate the physical and mechanical properties of recycled aggregates, such as particle size, porosity, and water absorption, must be performed before these materials are used in concrete mixtures [1].

Porosity and Water Absorption Capacity

One of the main disadvantages of recycled aggregates is their higher porosity compared to natural aggregates. Higher porosity indicates more void spaces within the material, allowing more water to be absorbed into the aggregate. This has the potential to reduce the mechanical strength of recycled concrete, especially the compressive and flexural strengths. In concrete, water absorbed by recycled aggregates not only reduces the amount of water available for the cement hydration process but also increases the risk of long-term damage due to freeze-thaw cycles [5].

The porosity of recycled aggregates can also reduce the bond between cement paste and aggregates, which is important for ensuring the mechanical strength of concrete. When the cement paste is unable to fill the voids in the aggregates properly, the concrete becomes more susceptible to cracking and structural damage. Therefore, more in-depth research is needed to understand how porosity and water absorption affect the performance of recycled concrete under various environmental conditions.

One proposed solution to overcome the porosity problem is the use of superplasticizers, additives that help increase the density of concrete and reduce the water requirement in the mixture. Superplasticizers can improve the distribution of water in the concrete mixture, thereby reducing the risk of damage caused by high porosity [1]. In addition, the use of alternative binders such as fly ash or geopolymer cement can help improve the bond between recycled aggregate and cement paste, which ultimately increases the mechanical strength of recycled concrete [2].

Mechanical Performance: Compressive and Flexural Strength

The mechanical performance of recycled concrete with rigid pavement waste is often a major concern, especially in terms of compressive and flexural strength. The use of recycled aggregates in high proportions (more than 60%) often results in a decrease in the compressive and flexural strength of concrete. Studies have shown that the higher porosity of recycled aggregates, as well as their greater water absorption, reduces the bond between cement paste and aggregate, resulting in a decrease in the mechanical strength of concrete [5].

Compressive strength is one of the main parameters used to determine the ability of concrete to withstand compressive loads. Recycled aggregates with high porosity cause concrete to become more brittle, making it unable to withstand the applied load properly. This decrease in compressive strength can affect its application in projects that require high-strength concrete, such as road pavements and bridges.

In addition to compressive strength, flexural strength is also an important aspect in concrete applications, especially in projects involving dynamic loads, such as highways and bridges. Recycled concrete with a high proportion of recycled aggregates is more susceptible to cracking due to flexural loads, especially if the bond between the cement pastes and the aggregates is not strong enough. To overcome this problem, studies have shown that the addition of reinforcing fibers, such as steel fibers or polymer fibers, can help improve the flexural strength of recycled concrete [2]. These fibers act as additional reinforcement that helps resist cracks that may occur due to dynamic or flexural loads, thereby extending the life of the concrete.

Resistance to Freeze-Defreeze Cycles

The resistance of recycled concrete to freeze-thaw cycles is another challenge that needs to be considered, especially in areas with extreme climates. Freeze-thaw cycles cause water absorbed in the pores of the concrete to freeze and expand, which can produce internal stress in the concrete and cause cracks and structural damage [17]. Concrete with recycled aggregates that have higher porosity is more susceptible to damage caused by freeze-thaw cycles [12].

To address this issue, it is necessary to test the resistance of recycled concrete to freeze-thaw cycles under actual field conditions. Large-scale field tests are essential to evaluate the long-term durability of recycled concrete under varying climate conditions. Studies have also shown that the use of alternative binders, such as geopolymer cement, can help improve the resistance of concrete to freeze-thaw cycles, as this material has properties that are resistant to extreme temperature changes [1].

In addition, the use of additives such as concrete sealants or surface coatings can help reduce water penetration into the concrete, thereby reducing the risk of damage from freeze-thaw cycles. By using these additives, recycled concrete can have better resistance to harsh environmental conditions, thereby extending the life of concrete in structural applications [5].

Innovation in Concrete Mix Design

Innovation in concrete mix design is essential to overcome the mechanical performance weaknesses of recycled concrete. One of the most promising innovations is the use of reinforcing fibers in recycled concrete mixes. Steel fibers or polymer fibers can help strengthen the bond between cement paste and aggregate, and improve the concrete's resistance to dynamic and flexural loads. Studies have shown that the addition of steel fibers to recycled concrete mixes can increase flexural strength by 15-20%, depending on the proportion of fibers used [5].

In addition, the use of alternative binders such as geopolymer cement or fly ash can also improve the mechanical performance of recycled concrete. Geopolymer cement, which has lower carbon emissions compared to Portland cement, offers additional benefits in terms of environmental sustainability. The use of this material in recycled concrete can not only improve the compressive and flexural strength but also help reduce the environmental impact of concrete production [2].

Implications for Sustainable Development

The use of rigid pavement waste as recycled aggregate in concrete has significant implications for sustainable development. By reducing the need for virgin aggregate, recycled concrete helps mitigate the impacts of aggregate mining, such as land degradation and habitat loss. In addition, the use of rigid pavement waste also helps reduce construction waste that must be disposed of in landfills, thereby reducing pressure on increasingly limited landfill space [1].

In addition to environmental benefits, the use of rigid pavement waste in recycled concrete also provides economic benefits. The recycling process of this material can reduce the cost of concrete production, especially if the recycled material is available in large quantities near the construction project site. Thus, recycled concrete not only provides a sustainable solution, but is also economical in the long term [2].

However, the success of large-scale recycled concrete applications depends on innovations in concrete mix design, the development of more efficient demolition technologies, and regulations that support the use of recycled materials in construction projects. Therefore, further research and large-scale field testing are needed to ensure that recycled concrete with rigid pavement waste aggregates can meet the mechanical strength and long-term durability standards required in various infrastructure applications [5].

CONCLUSION

The conclusion of this review shows that the use of rigid pavement waste as recycled aggregate in concrete is a promising innovation to improve sustainability in the construction industry. Although the use of this waste offers several advantages, such as reducing construction waste and reducing the exploitation of natural aggregates, challenges related to the mechanical performance of recycled concrete still need to be overcome. The main challenges faced are the reduction in flexural strength and resistance to freeze-thaw cycles, especially when the proportion of recycled aggregate used is quite high. However, through innovations such as the addition of reinforcing fibers, either made of steel or polymer, and the use of alternative binders such as geopolymer cement and fly ash, the mechanical performance of recycled concrete can be significantly improved. The development of more efficient crushing technologies and the implementation of recycled aggregate quality standards are also important to ensure that the recycled aggregate produced is of acceptable quality in structural applications. Furthermore, these innovations not only have the potential to improve the compressive and flexural strength of recycled concrete, but also can extend the concrete's life and improve its

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resistance to harsh environmental conditions and dynamic loads. To improve the effectiveness of the use of rigid pavement waste, further research is needed that focuses on the use of reinforcing fibers and alternative binders in recycled concrete mixtures. This research should explore how steel fibers or polymers can improve flexural performance, as well as how binders such as geopolymer cement or fly ash can improve the overall mechanical strength of concrete. In addition, the development of more efficient crushing technologies is needed to ensure that the recycled aggregates produced have good quality. Technologies that can reduce porosity and increase the bond between cement paste and aggregate will be a crucial solution in improving the performance of recycled concrete, in addition, this technology must also be energy efficient to support sustainability in terms of the environment and production costs. Large-scale field testing is essential to ensure that recycled concrete with these innovations can perform well in the long term in real environments. Field tests involving resistance to freeze-defrost cycles, dynamic loads, and temperature changes should be an important part of this evaluation. Furthermore, the development of regulations and standards that support the use of recycled materials in the construction sector needs to be accelerated by the government and related authorities. The standard should include recycled aggregate quality criteria, evaluation methods, and guidelines for appropriate mix proportions, so that the adoption of recycled materials can be carried out without compromising construction quality and safety. Finally, education and awareness raising on the importance of sustainability in the construction industry is urgently needed. Education involving various stakeholders such as engineers, contractors, and project authorities will accelerate the adoption of innovations in the use of recycled materials. Through this awareness raising, the construction sector can more quickly shift to more environmentally friendly practices and support sustainability. By implementing all these steps, the innovation of using rigid pavement waste in recycled concrete can be an important solution in improving the mechanical performance of concrete, extending the structural life, and making a significant contribution to the development of more environmentally friendly infrastructure.

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