

# Comprehensive Analysis of Roller-Compacted Concrete for Road Infrastructure: Materials, Performance, and Applications in the Sub-Saharan Context

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## Abstract

Road infrastructure is crucial for economic and social development, especially in Sub-Saharan Africa, where it ensures connectivity and mobility. However, bituminous pavement deterioration is common due to harsh climates and inadequate adaptation of materials and techniques. This highlights the need for innovative and durable solutions. Roller-Compacted Concrete (RCC), a no-slump concrete compacted with vibratory rollers, offers a promising alternative. Known for its strength, durability, and cost-efficiency, RCC has seen growing global interest but remains underutilized in Burkina Faso and other regions. This paper presents a comprehensive analysis of the use of RCC in pavement applications. It examines constituent materials, mix design approaches, and mechanical and durability performance under various environmental conditions. Recent advancements and practical applications are also discussed. The study identifies research gaps and concludes with recommendations to support the adoption of RCC technology in Sub-Saharan Africa's road construction sector.

## Keywords

Roller-Compacted Concrete, Pavement, Road Materials, Mix Design, Mechanical Properties

## 1. Introduction

Road infrastructure plays a crucial role in economic, social, and environmental

development of nations worldwide. As a vital vector of connectivity, roads facilitate the transportation of goods and people, promote regional integration, boost trade and tourism, and provide essential access to healthcare, education, and employment. Moreover, efficient road networks help reduce regional disparities by connecting rural and remote populations to urban centers and markets.

However, to ensure that roads can perform their intended functions effectively, the quality and durability of their pavement must be guaranteed. The unit costs of road construction and maintenance are extremely high. For example, in Burkina Faso, as in many other Sub-Saharan African countries, donors estimate that the cost of constructing one kilometer of paved roads ranges between USD 290,639 and 401,646, while rehabilitation can cost nearly as much (USD 299,551 to 352,613 per km) [1]. Thus, Roller-Compacted Concrete (RCC) offers significant potential.

RCC is an advanced construction technique that is known for its strength, durability, and high performance. This involves compacting a layer of fresh concrete on-site using static or vibratory rollers. This concept originated in the 1930s when engineers began experimenting with the layered compaction of concrete using rollers. However, RCC gained momentum only in the 1970s with large infrastructure projects, such as dams and levees [2]. One of the earliest notable applications of RCC was in dam construction, where its rapid placement and efficient compaction over large surfaces are particularly advantageous.

Since then, RCC has expanded into other construction sectors, including roads, parking lots, industrial platforms, and airport runways. In road construction, RCC provides a smooth, uniform surface that can withstand heavy traffic, harsh weather conditions, and natural wear. Its superior resistance reduces the frequency of repairs and extends pavement lifespan, resulting in significant savings in maintenance and rehabilitation costs.

The objective of this study is to compile and synthesize the current knowledge on the use of RCC in road construction, providing valuable and up-to-date insights. By presenting an overview of the fundamental principles, constituent materials, manufacturing processes, and mechanical properties of RCC, this review aims to highlight knowledge gaps and identify areas for further research.

## **2. Application of RCC for Pavement Construction**

The construction of RCC pavements involves a series of coordinated operations designed to ensure structural integrity, uniformity, and long-term performance of pavements. These processes include proportioning and mixing, subgrade and base preparation, transportation, placement, compaction, joint construction, and curing [3].

The process begins with the precise batching of RCC constituents (cement, aggregates, water, and admixtures) according to the prescribed mix design. The uniform dispersion of these components during mixing is essential for achieving homogeneity and consistency. The mixing duration must be adapted to the charac-

teristics and proportions of the materials used and should be validated by uniformity tests (e.g., gradation and strength) performed at both the front and rear of the batch. These controls help define the appropriate batch sizes and mixing times for specific aggregate blends.

Subsequently, subgrade and base layers were carefully prepared. According to ASTM D1557 [4], the subgrade should be compacted to at least 95% of the maximum dry density. The underlying layers must exhibit sufficient stiffness and bearing capacity to support the RCC compaction. Prior to placement, the paving area must be graded according to the specified elevations and tolerances outlined in the design documentation.

RCC is generally transported from mixing plants to paving sites using dump trucks. Care must be taken during loading and transport to prevent segregation, which can compromise the homogeneity and performance of the final product.

For placement, RCC is commonly laid using modified asphalt pavers, which are capable of managing the high-volume, stiff consistency of the RCC mix. The paver must be able to spread concrete uniformly and achieve at least 80% of the target wet density prior to compaction.

Compaction is a critical phase because it directly influences the final density, strength, permeability, and surface quality of the pavement. Unlike conventional concrete, RCC is not placed within the formwork and does not require reinforcement. Instead, compaction is achieved using heavy vibratory steel drum rollers, which are often supplemented by rubber-tired rollers. A 10-ton dual-drum vibratory roller is typically used immediately after placement. The final roller passes help seal the surface imperfections and ensure a smooth finish [3].

When successive paving lanes are placed in quick succession, fresh joints can be formed by simultaneously compacting adjacent lanes, thereby creating a monolithic bond without the need for additional joint treatment.

Curing is an essential component of RCC pavement construction, which directly affects strength development and durability. Given that RCC exhibits no bleed water, it is highly susceptible to early age moisture loss, which can result in surface shrinkage cracks and micro-fissures. Effective curing strategies aim to retain the internal moisture. These may include moist curing, applying water via spray bars for at least seven days, or the use of a white-pigmented curing compound in compliance with ASTM C309 [5] to form a sealing barrier that minimizes evaporation.

Each of these construction phases must be rigorously controlled to ensure that the RCC pavement performs reliably under service conditions, thereby providing a cost-effective, durable, and low-maintenance alternative to conventional paving systems.

### **3. Materials and Composition of RCC**

RCC comprises several key components that influence its mechanical properties, durability, and performance in the field. These constituent materials were care-

fully selected to ensure the quality and strength of the final concrete.

### 3.1. Binders

RCC requires the use of cement types that are specifically suited to their particular placement conditions and durability requirements. Cement is the primary binding material in the mix, providing the RCC with mechanical strength and structural integrity. Commonly used cements include:

- Ordinary Portland Cement (CEM I) is valued for its high early strength, although it is less suitable for mass concrete because of its high heat of hydration.
- Portland Composite Cement (CEM II), which contains supplementary materials, such as fly ash or slag, is widely used to improve durability and cost efficiency.
- Blast Furnace Slag Cement (CEM III) is preferred in RCC if it is subjected to thermal or chemical stress because of its low heat of hydration and long-term strength.
- Pozzolanic Cement (CEM IV), which incorporates natural or industrial pozzolans, enhances resistance to aggressive environments while reducing carbon emissions.

Ordinary Portland Cement (OPC) remains the primary binder in RCC mixtures [6]-[8]. However, several studies have explored the partial replacement of OPC with supplementary cementitious materials (SCMs) such as silica fume, nano-silica, natural pozzolans, fly ash, and rice husk ash to improve durability, reduce the carbon footprint, and enhance the long-term performance [9]-[14]. The use of nano-SiO<sub>2</sub>, in particular, has been shown to refine the microstructure and enhance the early strength development [9] [12].

In addition, non-traditional binders have been investigated. For example, cationic asphalt emulsion has been used as a partial cement replacement to improve workability and reduce compaction energy [15], whereas alkali-activated binders have demonstrated potential for developing geopolymer RCC with improved environmental performance [16].

Mineral admixtures are widely recognized in the construction industry as finely ground materials capable of imparting specific performance characteristics to concrete. In the context of RCC, these additions contribute to improved workability in the fresh state, enhanced durability in the hardened state, and increased compactness. They also serve as fine components in the mix when the natural fines content is insufficient, and generally possess pozzolanic and/or hydraulic reactivity.

The most commonly used mineral admixtures are fly ash, ground granulated blast furnace slag (GGBFS), silica fume, ground quartz, and metakaolin. Agricultural residues, such as sugarcane bagasse ash and rice husk ash, have also been investigated for their potential as sustainable supplementary materials [9] [10] [17] [18], offering environmental benefits and contributing to RCC sustainability.

In many sub-Saharan African countries, the choice of materials for RCC is influenced by both availability and cost constraints. Conventional cement remains expensive and is often imported, highlighting the importance of exploring alternative or supplementary binders. Lateritic soils, which are widely available across the region, can serve as aggregates or blend after treatment. Locally sourced pozzolans, such as calcined clays or agricultural by-products, such as rice husk ash, provide sustainable options to partially replace cement while maintaining performance.

Recent studies in Burkina Faso have contributed to the exploration of alternative binders for hydraulic concretes. Research has demonstrated the potential of supplementary cementitious materials, such as industrial by-products, to partially replace clinker in cement, thereby lowering the carbon footprint while maintaining mechanical performance and durability. These approaches have been successfully applied not only to conventional concretes but also to high strength concretes with enhanced long-term resistance [19]-[21]. In parallel, significant advances have been made in the development of geopolymer binders, which utilize locally available aluminosilicate sources and industrial residues, offering promising results in terms of strength, durability, and environmental sustainability [22]-[24]. Such innovations illustrate that the regional scientific community is actively contributing to the global effort of developing sustainable binders, while tailoring them to the specific material availability and climatic constraints of Sub-Saharan Africa.

These local materials not only lower production costs but also contribute to improved durability in hot, humid climates. Therefore, their proper characterization and integration into RCC are essential for their successful application in road construction.

### **3.2. Aggregates**

Aggregates form the supporting structures of concrete and contribute to its strength and durability. In RCC, aggregates are carefully selected for their size, shape, and composition to optimize the mechanical properties of the final concrete. Natural aggregates, such as crushed granite, gravel, and sand, remain the most commonly used components in RCC because of their availability and proven performance [6] [7] [25]. In most studies, a maximum aggregate size of 19 - 20 mm is adopted to ensure adequate compaction and uniformity [6] [8].

Recent research has increasingly focused on incorporating recycled and waste materials as partial or full replacements for natural aggregates. Recycled concrete aggregates (RCA) have been employed in several studies with promising results in terms of mechanical strength and environmental impact [8] [10] [26] [27]. Similarly, recycled asphalt pavement (RAP) has been used effectively, either alone or in combination with other supplementary materials, to enhance the sustainability of RCC pavements [10] [28] [29].

The incorporation of waste rubber aggregates obtained from shredded tires has

also gained attention. These aggregates offer advantages such as reduced density and improved toughness, although challenges remain with respect to bonding and stiffness [11] [30]. Innovative treatments, such as sand coating of rubber particles, have been suggested to improve the interfacial bonding [30]. Other unconventional aggregates investigated include brick powder, glass powder, steel slag, and waste glass, which not only help divert waste from landfills, but also contribute to acceptable mechanical performance when used in optimized proportions [18] [31].

### 3.3. Admixtures

Chemical admixtures have also been employed to modify RCC properties. Water-reducing and retarding admixtures can enhance cohesiveness, aid in compaction, and extend the workability of RCC beyond the typical 45 min to 1 h, which is particularly beneficial during hot weather, longer haul distances, and placement of thick lifts. Superplasticizers, such as polycarboxylates, have been used in dry batch plant production to improve workability and reduce mixing times, resulting in significantly increased production rates. However, the excess use of superplasticizers causes the presence of excess water that fills the pore volume, which leaves voids in the hardened roller compacted concrete matrix by drying, and then microcracks develop in the concrete during loading, premature fracture occurs, and bending strength is reduced [32].

Air-entraining admixtures, though not commonly used in RCC, can improve freeze-thaw durability by introducing tiny air bubbles that enhance resistance to frost-induced microcracking and de-icing salt scaling.

## 4. Mix Design Method

RCC formulation methods can be classified into three distinct categories: empirical, semiempirical, and theoretical.

### 4.1. Empirical Methods

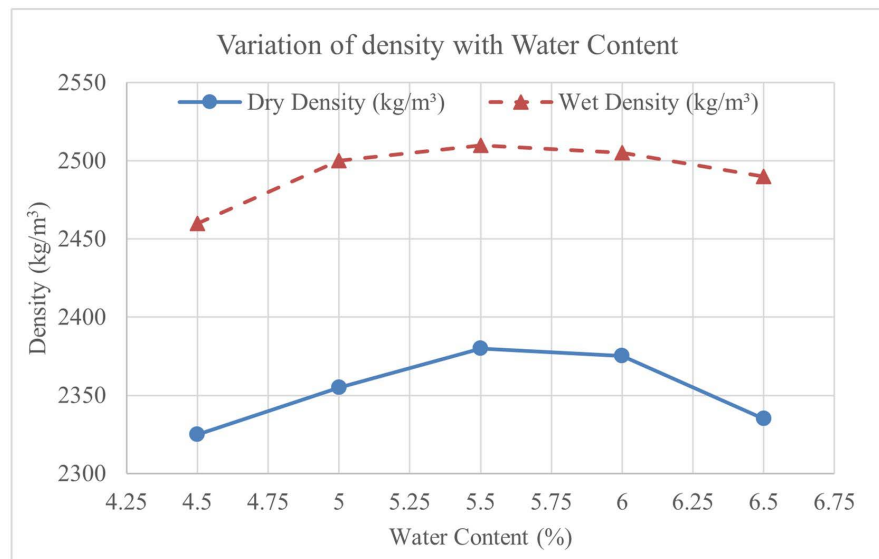
Empirical mix design methods for RCC rely on an experimental laboratory-based approach, in which a series of trial mixtures is prepared to identify the optimal composition. These methods are often time-consuming and resource-intensive, and sometimes require more than 25 mix iterations to achieve the desired mechanical and workability properties. On-site adjustments are frequently necessary and require substantial expertise in RCC to minimize the number of trials and errors.

Among the most commonly applied empirical approaches, two have been described as particularly effective by the ACI Committee 325.10R-14 [33]: the consistency-based method and geotechnical approach.

The consistency-based method aims to achieve the maximum density with the minimum possible paste volume, thereby ensuring adequate consistency. Several trials were conducted by varying the water-to-cement (w/c) and sand-to-cement (s/c) ratios until the desired mechanical strength and workability were reached.

The objective was to determine the combination of these ratios that yielded the highest dry density while minimizing the paste content.

The geotechnical method is based on principles derived from soil mechanics, focusing on optimizing compaction to achieve the maximum dry density and favorable mechanical performance. This approach involves evaluation of the relationship between the dry density and moisture content of the RCC mix, as illustrated in **Figure 1**. It is particularly well suited for mixtures containing fine aggregates and a higher binder content, making it especially relevant in road construction applications. However, a key limitation of this method is that it does not always result in a truly optimized mix composition, as it may overlook certain performance criteria beyond the compaction efficiency [34].



**Figure 1.** Relationship between density and water content of mixtures [34].

## 4.2. Semi-Empirical Methods

Semi-empirical methods for designing RCC combine the theoretical principles of granular material mechanics with experimental adjustments. These approaches are based on compaction models, such as the particle packing theory, to optimize the aggregate distribution and achieve the maximum density of the granular skeleton. They help to reduce the number of required laboratory trials while maintaining a degree of flexibility in adjusting the mix design parameters. Verification tests are still necessary, but their number is generally reduced because of the predictive efficiency of the model.

## 4.3. Theoretical Method

Among the most well-known approaches is the particle packing method developed by de Larrard, which relies on a mathematical model to estimate the maximum packing density based on the particle size distribution of materials. This method enables rational optimization of the mix by minimizing the required paste

volume while ensuring adequate workability and satisfactory mechanical performance.

Designing RCC mixtures in the Sub-Saharan context requires careful consideration of both the performance requirements and resource limitations. High ambient temperatures accelerate hydration, which can reduce workability and complicate compaction if not properly controlled. Indeed, studies have shown that an increase in temperature (above 40°C) reduces physical and mechanical performance due to the malformation of hydration products [35]. To address this, mix designs should emphasize adequate moisture control and the use of supplementary cementitious materials to moderate the heat release. The use of metakaolin has shown promising results and could support the development of RCC in the Sub-Saharan region by reducing the risk of early-age cracking associated with high shrinkage [36]. In Burkina Faso, where rainfall is concentrated and often intense during the wet season, achieving low-permeability mixtures is critical to minimize water infiltration and surface erosion. Aggregate gradation is also influenced by the widespread use of lateritic soils and crushed rock, which differ from conventional aggregates in temperate regions. Adapting RCC mix design to these conditions, through optimization of the water-to-binder ratio, the integration of local pozzolanic materials, and ensuring sufficient fines content, is essential to produce durable and resilient pavements suitable for the regional environment.

## 5. Properties of RCC

### 5.1. Workability

Workability refers to the ease with which RCC can be placed and compacted, and it provides insight into the uniformity of the mix. It is governed by several inter-related factors, including the volume and fluidity of the cement paste and proportion of fines within the aggregate grading. A higher fines content typically enhances workability, as it increases the number of discontinuity points within the granular skeleton, allowing for greater mobility of the particles. Additionally, the shape, texture, and absorptivity of aggregates significantly influence the workability of RCC more than in conventional concrete. Rounded particles offer better workability than flat or elongated ones. Porous aggregates tend to absorb mixing water, thereby reducing workability, whereas rough-textured aggregates demand a higher volume of paste to achieve similar workability owing to their increased surface irregularities.

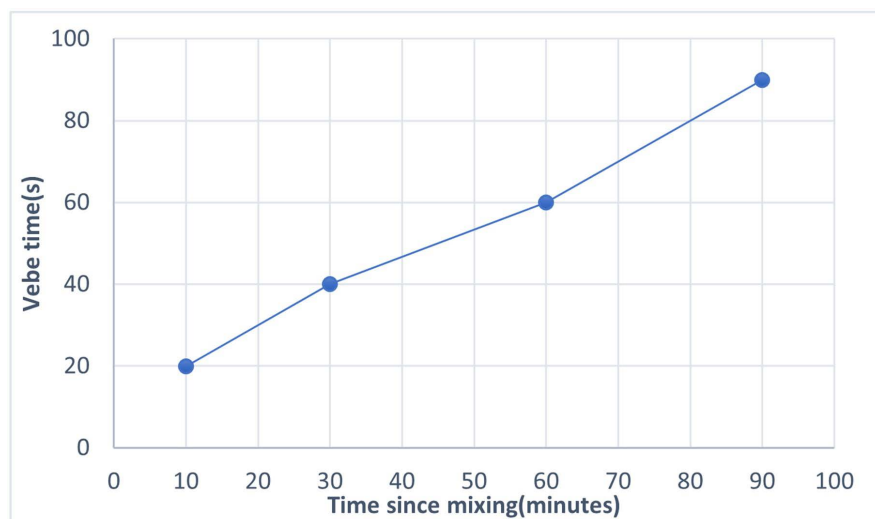
The overall quality of RCC is strongly linked to its workability in the fresh state, which is typically measured by Vebe time. The mix should neither be too dry nor overly fluid. Excessive workability often results in a higher water-to-cement (w/c) ratio, which negatively affects the mechanical strength and long-term durability of RCC [34]. Moreover, during placement, high fluidity can induce interstitial pore pressure under the compaction equipment, leading to excessive deformation and surface undulations. The increased stickiness of the paste can also cause it to adhere to the compactor drum, thereby further compromising the surface finish

quality.

On the other hand, low workability leads to higher residual air voids after compaction, which weakens the structural performance and durability of RCC. It may also cause material segregation, poor bonding between layers, and a rough, uneven surface texture.

Given the stiff nature of the RCC, the traditional slump test using the Abrams cone is not suitable. Instead, the Vebe consistency test was preferred. This test measured the time required to consolidate the concrete mix into a ring of mortar using vibration applied through a transparent Plexiglas plate with a surcharge of 22.7 kg. Vebe time corresponds to the duration required for the cement paste to fully fill the voids within the granular skeleton. For accurate readings, the vibrating table must be level and securely fixed on a solid concrete base to prevent movement during testing. The optimal Vebe consistency range for RCC is generally between 40 s and 90 s.

It is important to note that the Vebe time of the RCC mix increased with time from the initial contact between the water and binder. Hence, monitoring the evolution of workability from mixing to placement is essential to ensure consistent quality. **Figure 2** illustrates an example of how workability decreases (*i.e.*, Vebe time increases) as time elapses after mixing for RCC mixes prepared with 250 kg/m<sup>3</sup> cement, a water-to-binder ratio of 0.35, and a maximum aggregate size of 20 mm.



**Figure 2.** Evolution of workability of RCC over time [34].

## 5.2. Density

Density is a key performance parameter in RCC, as it directly influences the mechanical strength, durability, permeability, and surface quality. Achieving optimal density during compaction ensures an adequate load-bearing capacity and long-term performance of the pavement structure. A typical target is to reach at least 98% of the maximum dry density determined in the laboratory, most often using

the Modified Proctor test [4]. Several factors influence the in-place density, including the mix design parameters (such as aggregate grading, paste content, and moisture content), compaction energy, equipment type, and environmental conditions during placement.

Some studies have highlighted the influence of mixed constituents on the density-related properties. For instance, Modarres and Hosseini [10] reported that the use of reclaimed asphalt pavement (RAP) materials in RCC mixtures tends to reduce both the optimum moisture content and maximum dry density compared to conventional aggregates. Similarly, the addition of rice husk ash (RHA), which is characterized by a high specific surface area, increases the water demand of the mixture and leads to a reduction in the achievable dry density.

Furthermore, the density of RCC is closely linked to the volume of entrapped voids and the porosity of the hardened matrix. Arash *et al.* in [37] demonstrated that these parameters in RCC are generally comparable to those observed in conventional concrete. However, the typically lower water content and absence of intentionally entrained air in RCC mixtures often result in slightly higher in-place densities relative to conventional air-entrained mass concrete made with similar aggregates.

### 5.3. Segregation in RCC

RCCs are particularly vulnerable to segregation owing to their inherently low paste content and reduced mixing water volume. Segregation in RCC is influenced by several factors, including particle size distribution, maximum nominal aggregate size, and rheological characteristics of the paste. This can occur at any stage of handling during batching, transportation, placement, or compaction.

One of the most critical stages is the truck loading. To minimize segregation during transport, RCC should be discharged uniformly along the length of the dump truck bed, typically by placing one-third of the load at the front, one-third in the center, and the remaining third at the rear. If the RCC is improperly discharged into the truck (e.g., from a single point), vibrations and movements during transportation are likely to exacerbate aggregate separation, leading to non-uniform mixtures [17] [38].

Similarly, during placement, segregation must be minimized by maintaining a consistent and sufficient amount of material within the paver hopper. The RCC should be fed in a manner that prevents the hopper from running empty before the next batch is introduced. The concrete level in the hopper must always remain above the screw augers to avoid introducing air voids or uneven distribution [39].

Despite all the precautions, areas of localized segregation can still develop at the paver output, particularly along fresh transverse and longitudinal joints or at points of material restart. Field experience has shown that a practical mitigation method involves manually adding fine particles (typically < 5 mm) screened from fresh RCC to segregated zones before compaction. This technique helps to restore homogeneity in the mix and improves interparticle cohesion during roll-

ing [10].

Critical areas such as cold joints, transverse and longitudinal construction joints, and areas of material restart require special attention. Proper preparation, cleaning, and sometimes the application of bonding agents or fresh mortar may be necessary to prevent weak zones and ensure structural continuity [38].

#### 5.4. Mechanical Properties

In the hardened state, the mechanical properties of concrete are the most critical indicators of its structural performance. Among these, the compressive strength is one of the most defining characteristics of RCC. Their ability to withstand high and concentrated loads is directly linked to their enhanced compressive strength, which distinguishes them from many conventional concrete types.

The compressive strength can be attributed to two primary factors: the high compactness of the granular skeleton and the low water-to-cement ratio (W/C). The high compactness of the granular skeleton in RCC results in a denser aggregate arrangement and an interlocked structure that significantly enhances the mechanical resistance by improving the aggregate interconnectivity and reducing the volume of voids within the mixture. According to de Larrard's packing model [40], optimizing the particle size distribution results in a tightly packed granular matrix, minimizing the amount of cement paste required to fill voids and thereby reducing porosity. This denser internal structure directly contributes to a higher load-bearing capacity because the aggregates can efficiently resist and transfer applied stresses without relying solely on the cementitious matrix.

Moreover, the compact structure enhances the internal resistance to crack propagation, particularly microcracks initiated by drying shrinkage in the cementitious paste. Consequently, the post-cracking behavior and overall compressive strength of the hardened concrete were significantly improved.

A low W/C ratio generally leads to a reduction in the capillary porosity of hardened cement paste, resulting in a denser and stronger microstructure. This is especially important in RCC, which typically contains minimal paste and relies heavily on the quality of the bond between the paste and the aggregate. According to Mehta and Monteiro [41], a lower W/C ratio enhances the degree of hydration within a limited water volume, producing a refined pore structure and fewer interconnected voids, which contributes significantly to a higher compressive strength.

In RCC, where compaction replaces much of the conventional workability requirements, the use of a low W/C ratio (typically between 0.30 and 0.45) is common and advantageous. Rahmani *et al.* [42] demonstrated that decreasing W/C ratio from 0.55 to 0.3 early doubles the compressive strength, highlighting the substantial influence of water availability on cement hydration and paste development. A reduction in the W/C ratio leads to a decrease in the amount of free water and an increase in the compressive strength. Similarly, a higher W/C ratio negatively impacts the stiffness, as the static modulus of elasticity decreases by 32%

when W/C increases within the same range (Figure 3).

The low water content also minimizes the drying shrinkage and reduces the risk of microcracking, which contributes to the long-term strength development and durability of the pavement.

However, it is essential to balance the W/C ratio with an adequate compaction energy. As highlighted by the ACI Committee [38] excessively low W/C ratios without proper compaction can lead to poor particle dispersion and incomplete paste coating, thereby resulting in local weaknesses. Therefore, the success of low-W/C mixes in RCC depends on the effective compaction and optimal aggregate gradation, ensuring uniform distribution and hydration.

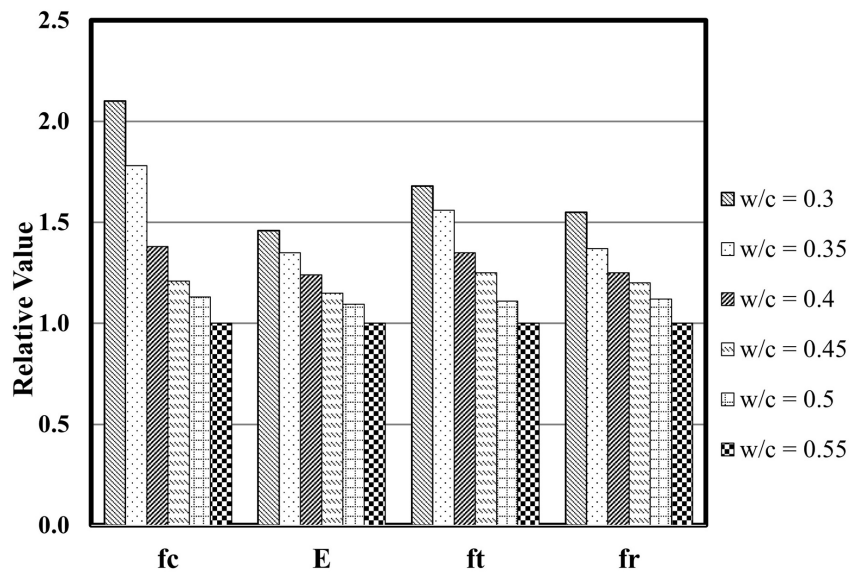


Figure 3. Variation of mechanical properties with W/C ratio [42].

Studies have also demonstrated that cement content plays a pivotal role in determining the mechanical properties of RCC. As the primary binder, cement significantly influences both the compressive and flexural strengths by controlling the development of the cementitious matrix and the degree of bond between the aggregates. An increase in the cement content generally leads to a higher compressive strength owing to improved paste cohesion and reduced porosity in the interfacial transition zone. This follows from the fact that the mixture with a higher cement content has a higher total volume of adhesive paste; therefore, the mixture has better homogeneity [11] [32] [42].

RCC is characterized by a dense, aggregate-rich matrix in which the volume of aggregates exceeds that of conventional concrete by approximately 10% - 15%. This higher aggregate content creates favorable conditions for the incorporation of alternative aggregates, such as recycled concrete aggregates, reclaimed asphalt pavement, electric arc furnace steel slag, or shredded tire rubber, without significantly compromising mechanical performance [43]. However, a large ratio is not recommended for replacing RCC because it tends to degrade the mechanical properties of concrete.

For example, the compressive strength was reduced by more than 30% when the ratio of recycled concrete aggregates was 100% [8] [11] [28] [44].

### 5.5. Fatigue Behavior

The fatigue behavior of RCC is a critical performance parameter, particularly for pavement applications subjected to repeated traffic loads over time. Fatigue in concrete refers to the progressive deterioration of material strength owing to cyclic loading, which may lead to cracking and eventual structural failure. RCC exhibits favorable fatigue resistance primarily because of its high density and low water-to-cement ratio (W/C), which limits microcrack propagation and improves internal cohesion. Research has demonstrated that RCC can achieve comparable or superior fatigue performance to conventional concrete when optimally compacted [45] [46]. Moreover, the absence of entrained air and the use of a well-graded granular skeleton contribute to the ability of the material to resist stress reversal. RCC pavements with adequate flexural strength and proper curing exhibit extended fatigue life under highway loading conditions. Fatigue resistance is also influenced by factors such as cement content, curing duration, layer thickness, and the incorporation of supplementary cementitious materials, such as fly ash or slag, which improve the microstructure and toughness. Recent studies have explored the use of fiber reinforcement in RCC to enhance the fatigue life by bridging cracks and dissipating energy under repeated loading [18] [47]. Overall, fatigue performance is a key design consideration for RCC pavements, and should be integrated into structural evaluations, particularly for heavily trafficked roadways and industrial slabs.

Park *et al.* [48] found that after a set of numerical analyses, the failure modes of RCC for a given loading condition appeared to be four-directional bottom-up cracks because of a uniform fatigue load from the center. They developed a fatigue equation based on the relationship between the stress level and number of load repetitions (Figure 4).

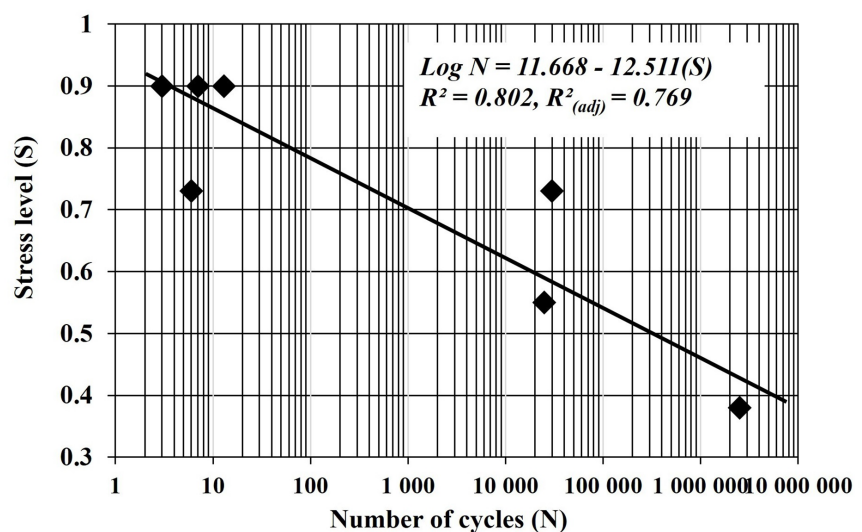


Figure 4. RCC fatigue regression curve and equation [48].

## 5.6. Durability

Permeability is a key indicator of the long-term durability of RCC, as it directly influences the resistance of the material to fluid ingress, freeze-thaw cycles, and chemical attacks. The permeability of the RCC is primarily controlled by the compacted void content and porosity of the mortar matrix. These parameters are in turn influenced by the mixture design, pavement techniques, and compaction efficiency during construction [2]. A well-compacted RCC mix with an adequate paste content can achieve permeability values similar to those of conventional concrete.

Ghahari *et al.* [14] investigated the use of natural trass pozzolans and air-entraining agents. They found that although the low pozzolanic activity of Trass initially resulted in higher permeability, the water penetration depth was reduced by 14% at 90 days compared to plain concrete. The incorporation of air-entraining agents further improved impermeability, suggesting a synergistic effect on pore structure refinement. The orientation of the water penetration also plays a role. Researchers have demonstrated that permeability is higher when the direction of water flow is parallel to the casting layers owing to the presence of cold joints between successive lifts, which is a typical issue in RCC placement [37].

Pozzolanic and recycled materials have also been explored for their effects on the permeability. Rad and Modarres [49] reported that incorporating 3% coal waste ash (CWA) reduced the volume of permeable voids owing to finer particle packing and improved interfacial transition zones. However, increasing the CWA content beyond this threshold reversed this trend, indicating a dilution effect on the cement hydration. In a similar study, Ahmad *et al.* [50] found that increasing Lumachelle fine aggregates led to greater water penetration, while the use of pozzolanic materials decreased permeability in most cases.

Aghaeipour and Madhkhan [51] evaluated the influence of ground granulated blast furnace slag (GGBFS) on RCC and observed that permeability decreased with 20% and 40% replacement levels but increased again at 60%, likely due to a lack of sufficient clinker content to ensure proper hydration. They also noted that increasing the total cementitious content from 12% to 15% reduced the permeability, reinforcing the importance of binder dosage to ensure durability.

The resistance of RCC to abrasion and erosion is a key factor for their application in industrial and heavy-duty pavements. It has been well established that the compressive strength and aggregate quality are the primary drivers of abrasion resistance. Studies conducted on RCC exposed to aggressive environments, such as log yards and coal storage sites, report minimal surface degradation under intense mechanical stress [2]. Experimental investigations by Rao *et al.* [52] confirmed that the inclusion of mineral admixtures such as GGBS and fly ash does not diminish surface performance, provided that a high compressive strength is maintained. In both GGBS- and fly ash-based RCC mixes, abrasion resistance increased steadily with curing time, showing limited sensitivity to variations in the mineral admixture content or M-sand proportion.

This reinforces the role of compressive strength as a dominant factor in abrasion performance, more so than that of flexural strength. Moreover, Wang *et al.* [53] revealed that distorted concrete, a variation of a modified internal structure, could outperform RCC in erosion resistance, suggesting further avenues for structural optimization. Other authors also reported improved durability with the use of silica fume and finely ground cement, which helps reduce permeability and, indirectly, erosion susceptibility [37]. These findings collectively highlight the importance of optimizing the mix design and curing conditions to enhance the surface durability, particularly in environments where mechanical wear and fluid action are significant.

## 6. Recent Developments and Research Perspectives in RCC

In recent years, RCC has undergone significant advancements, driving technology towards new frontiers and stimulating growing interest in research and innovation. A notable development has been the emergence of novel cement types and binder systems that provide enhanced performance in terms of strength, durability, and environmental sustainability. Low-clinker cements and geopolymer binders, for instance, offer high compressive strength and improved resistance to harsh conditions, such as freeze-thaw cycles and chemical attacks [13] [16]. Moreover, these materials contribute to a significant reduction in the carbon footprint by incorporating industrial by-products, such as fly ash and slag, while maintaining optimal performance in road applications.

The use of recycled and lightweight aggregates has also been explored to improve RCC's mechanical and thermal properties [47]. Simultaneously, advanced compaction technologies, (laser-assisted and electromagnetic compaction) aim to enhance concrete densification while reducing energy consumption [37]. Additionally, the development of prefabrication methods and rapid placement techniques is being considered to reduce the construction time and minimize site disruptions.

Despite these advances, several research gaps remain in the literature. Addressing these factors is crucial for optimizing RCC performance, particularly under Sub-Saharan conditions. Addressing these factors is essential to optimize RCC performance, particularly under the climatic, material, and economic conditions of Sub-Saharan Africa. Key areas include:

- Long-term durability and degradation mechanisms: Limited data exist on how RCC behave under real-life traffic loading, moisture variations, and aggressive environments typical of the region.
- Climate resilience: Adaptation of RCC mix designs to withstand extreme heat, intense rainfall, and chemical exposure remains underexplored.
- Local material optimization: Systematic studies are needed on the use of latent aggregates, recycled materials, and industrial by-products readily available in Sub-Saharan Africa.
- Surface performance: Research on novel surface finishes, texturing, and pro-

TECTIVE coatings to improve skid resistance, durability, and maintenance is still limited.

- Construction technologies: Evaluation of advanced compaction methods, prefabrication, and rapid placement techniques in low-resource contexts is lacking.
- Design and modeling tools: More robust predictive models and simulations are required to accurately assess mechanical behavior and structural performance under local service conditions [54] [55].
- Implementation frameworks: Studies on quality control protocols, workforce training, and cost-benefit analyses tailored to Sub-Saharan Africa are still scarce.

By explicitly addressing these gaps, future research can accelerate RCC's transition from a promising alternative to a mainstream pavement solution, while ensuring its adaptation to regional needs and constraints.

## **7. Comparative Perspective on Pavement Options in Sub-Saharan Africa**

When evaluating pavement options for Sub-Saharan Africa, RCC must be considered in comparison to bituminous pavements and conventional concrete pavements. Bituminous pavements remain the most widely used because of their relatively low initial cost and ease of placement. However, in the Sub-Saharan context they are highly vulnerable to rutting, stripping, and rapid deterioration under high temperatures and intense rainfall. This results in frequent maintenance cycles and higher long-term costs. In contrast, conventional concrete pavements, offer superior durability and structural performance but are associated with high construction costs, longer curing periods, and the need for skilled labor, which can be limiting in resource-constrained environments.

RCC represents the middle ground between these alternatives [56]. Its placement with vibratory rollers allows for faster construction at a lower cost than conventional concrete, while offering significantly greater durability and resistance to climatic stresses than bituminous pavements. Although the initial investment in equipment and training can be substantial, the reduced maintenance requirements and extended service life of RCC make them economically attractive in a life-cycle cost perspective. In regions such as Burkina Faso, where budgetary constraints coexist with harsh environmental conditions, RCC can therefore provide a practical and sustainable compromise for pavement construction.

Beyond highway applications, Roller-Compacted Concrete (RCC) is particularly well-suited for roundabouts and parking areas in Sub-Saharan Africa. These facilities are subject to localized heavy stress owing to frequent braking, turning, and slow-moving traffic. In roundabouts, the continual lateral forces from heavy trucks often cause rutting and surface deformation in bituminous pavements, while RCC's high stiffness and resistance to shear stresses provide superior long-term performance. Similarly, in parking areas, especially those serving markets,

bus stations, and logistics facilities, RCC offers excellent durability against static loads and fuel or oil spillages that typically accelerate the degradation of bituminous surfaces.

The use of RCC in such contexts also aligns with cost and maintenance considerations. Roundabouts and parking areas are generally smaller in scale than long roadway sections, making the initial investment in RCC more manageable. Additionally, their strategic importance in traffic circulation and urban mobility implies that durability and reduced maintenance frequency translate directly into social and economic benefits. In the context of Burkina Faso, adopting RCC for these critical infrastructures could therefore serve as a highly visible demonstration of the technology's advantages while addressing pressing urban mobility challenges.

## **8. Practical Implementation Challenges of RCC in Sub-Saharan Countries**

Despite its technical advantages, the practical implementation of RCC in the Sub-Saharan countries such as Burkina Faso presents several challenges. The construction process requires specialized equipment, such as high-capacity mixers and vibratory rollers, which are not yet widely available in the region. This creates a dependency on imported machinery, potentially increasing project costs. In addition, successful RCC applications rely on precise placement, compaction, and curing practices, that require workforce training beyond conventional concrete construction techniques. Without adequate capacity-building, there is a risk of poor execution which could compromise performance. Furthermore, establishing reliable quality control protocols covering aspects such as moisture content, compaction degree, and surface finishing is critical but remains limited in local practice. Overcoming these barriers will require both institutional support and targeted investments to adapt RCC technology to the realities of road construction in Burkina Faso.

## **9. Conclusions**

Roller-Compacted Concrete (RCC) is a promising alternative to conventional pavement materials that offers a balance between mechanical performance, cost efficiency, and environmental sustainability. This study provides a comprehensive overview of RCC as a pavement material, examining the materials used, formulation principles, construction techniques, physical-mechanical properties, and evolving innovations.

Particular attention was given to local conditions in Sub-Saharan Africa, where climatic stresses, lateritic aggregates, and budgetary constraints create unique challenges and opportunities for RCC deployment.

Recent technological advances have transformed RCC into a sustainable and high-performance material. The use of low-clinker cements, geopolymers, industrial by-products, and recycled aggregates contributes to reducing the environ-

mental footprint while enhancing the durability under aggressive conditions. Applications such as highways, roundabouts, and parking facilities further demonstrate the versatility of RCC in addressing both structural and functional demands in the regional context.

Future research directions include long-term durability studies, advanced modeling of mechanical behavior, and adaptation to climate resilience. Understanding degradation mechanisms under real-life loading and environmental stresses is crucial for developing maintenance and rehabilitation strategies. The integration of smart technologies, predictive simulations, and sustainable materials will shape the next generation of RCC pavements.

The most critical step for accelerating RCC adoption in Sub-Saharan Africa lies in the development of regionally adapted design and construction guidelines supported by the research and pilot projects. Establishing demonstration sites in countries such as Burkina Faso would not only validate performance under real conditions but also facilitate workforce training, strengthen quality control protocols, and build confidence among decision-makers. With such initiatives, RCC can transition from a promising alternative to a mainstream solution, contributing significantly to the sustainability and resilience of road infrastructure in the region.

### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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