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A bibliometric analysis of pavement engineering research: Focus on composite and geosynthetic materials

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Highlights

- More effective than traditional reinforcement methods
- Eco-friendly and cost-efficient material solutions
- Reveals global research trends and collaborations in the field

Abstract

This study presents a bibliometric analysis of the literature concerning the reinforcement of subgrade and base layers in pavements using composite and geosynthetic materials. The durability and performance of pavements are directly related to the stability of the subgrade and base layers. Therefore, the reinforcement of these layers is crucial for extending road lifespan and reducing maintenance costs. Composite and geosynthetic materials offer superior mechanical properties, durability, and ease of application compared to traditional reinforcement methods. This bibliometric review is based on the analysis of publications obtained from the Web of Science databases. The study examines publication trends, top authors, institutions, countries, journals, and keywords. Additionally, citation analyses and network maps are used to assess the knowledge flow and interactions within the field. The analysis results demonstrate a growing interest in the use of composite and geosynthetic materials for reinforcing subgrade and base layers. Particularly, the use of materials such as geotextiles, geogrids, and fiber-reinforced composites is becoming widespread. Research shows that these materials increase soil bearing capacity, reduce deformation, and improve pavement performance. This study summarizes the current state and future research directions of composite and geosynthetic material usage in pavements. The findings provide valuable insights to guide researchers and engineering applications.

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1. Introduction

The establishment and sustained maintenance of robust and economically viable transportation infrastructures are indispensable for catalyzing economic advancement and bolstering societal prosperity, thus highlighting the pivotal role of ongoing innovation within the domain of pavement engineering [1]. Pavement structures, integral components of transportation networks, are routinely subjected to a complex interplay of vehicular loads, environmental factors, and evolving traffic patterns, which precipitate gradual degradation and eventual functional compromise [2]. To counter these challenges, pavement engineers are increasingly exploring advanced materials and techniques aimed at enhancing the load-bearing capacity, durability, and overall performance of pavement systems. Among these innovative approaches, the incorporation of composite and geosynthetic materials for the reinforcement of subgrade and base layers has garnered substantial attention [3]. Geosynthetic materials are frequently employed to reinforce pavement overlays, effectively mitigating crack propagation under the combined effects of repeated vehicular traffic and fluctuating thermal conditions [4]. Geosynthetics, including geotextiles and geogrids, have emerged as versatile solutions for improving the mechanical properties of soil and granular materials in pavement structures [5]. These materials offer a range of benefits, including increased tensile strength, improved load distribution, enhanced drainage, and reduced deformation [6]. By strategically incorporating geosynthetics into the subgrade and base layers, engineers can significantly enhance the structural capacity and extend the service life of pavements. The

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utilization of geosynthetics and composite materials represents a paradigm shift in pavement engineering, offering a sustainable and cost-effective means of enhancing the performance and longevity of transportation infrastructure [7]. The application of recycled materials, such as recycled high-density polyethylene strips, in cementitious matrices has also demonstrated effectiveness in stabilizing tensile crack propagation, contributing to the enhanced strength and toughness of composite materials used in pavement foundations [8]. This bibliometric analysis aims to comprehensively examine the existing body of knowledge pertaining to the reinforcement of subgrade and base layers using composite and geosynthetic materials.

1.1. Theoretical frameworks for geosynthetics and composite materials

The theoretical underpinnings of geosynthetic and composite material applications in pavement reinforcement are rooted in soil mechanics, structural mechanics, and materials science principles. The primary mechanisms by which these materials enhance pavement performance include: tension membrane effect, where the geosynthetic layer acts as a tensile reinforcement, resisting deformation and distributing loads over a wider area [9]; lateral confinement, which confines soil particles, increasing their shear strength and stiffness; and improved load distribution, where the geosynthetic layer spreads applied loads, reducing stress concentrations on the subgrade [10]. These reinforcement mechanisms contribute to improved pavement performance by increasing bearing capacity, reducing rutting, and extending service life. The effectiveness of geosynthetics in reinforcing soil structures is also influenced by factors such as soil type, geosynthetic properties, and installation techniques. The use of geosynthetics to reinforce the soil is an effective construction material to increase the bearing capacity and reduce the settlement of foundation resting on weak or poor soils [11]. When tensile stress occurs in the pavement layer due to vehicle loads, the geogrid resists these stresses, reducing pavement flexure and extending the road service life under the same traffic load [10]. For instance, the utilization of geogrid reinforcement in base layers results in layer coefficients falling within the range of 0.15 to 0.35, whereas geocell-reinforced base layers exhibit coefficients ranging from 0.175 to 0.425 [9]. When it comes to improving the bearing capacity of soils and to prevent failure in weak subgrades and increase the bearing capacity and decrease foundation settlement, geosynthetics are frequently utilized. The use of geogrids leads to a reduction in vertical stress on the subgrade, mitigating the risk of excessive deformation and failure. Additionally, geogrid reinforcement enhances the shear strength and stiffness of the base layer, contributing to improved overall pavement performance and durability.

1.2. Composite and geosynthetic materials for reinforcement

1.2.1 Geosynthetics

Geosynthetics are synthetic materials used to improve soil characteristics [12]. Geotextiles, geogrids, geonets, geomembranes, geocomposites, and geocells represent a wide range of materials that are used in geotechnical engineering applications, including pavement reinforcement [6]. Geotextiles are permeable fabrics used for separation, filtration, drainage, reinforcement, and stabilization [13]. Geogrids are grid-like materials with high tensile strength used for reinforcement and stabilization of soil. Geonets are net-like materials used for drainage and filtration. Geomembranes are impermeable sheets used for containment and barrier applications. Geocomposites combine different types of geosynthetics to provide multiple functions. For instance, woven coir geotextiles have demonstrated effectiveness in improving the California Bearing Ratio of soil, potentially eliminating the need for a strong base course in unpaved roads [14]. Geocells are three-dimensional cellular structures used for soil stabilization and confinement. Many state highway agencies conventionally accept the practice of using cementitious materials to treat or stabilize the poor subgrade [7]. However, some agencies and contractors are now using geosynthetics to improve the subgrade by providing separation, filtration, and reinforcement functions [6]. The use of geosynthetics in pavement reinforcement offers several advantages, including increased load-bearing capacity, reduced rutting, improved resistance to cracking, and extended service life [15]. It's worth noting that the deformation of pavement layers does not need to be significant to mobilize reinforcement. The arrangement of geosynthetic reinforcement, along with its type and placement, has been found to directly influence the extent of lateral movement within base courses, with maximum movement occurring directly beneath the center of the loading plate [7].

1.2.2 Composite materials

Composite materials offer a wide range of options for enhancing the performance and durability of transportation infrastructure components. These materials are engineered combinations of two or more distinct materials, each with its own set of physical and chemical properties, to create a new material with superior characteristics. Fiber-reinforced polymers, which combine high-strength fibers with a polymer matrix, are extensively employed in the rehabilitation and strengthening of concrete structures. Recycled materials, such as reclaimed asphalt pavement and recycled concrete aggregate, can be incorporated into composite materials to promote sustainability and reduce environmental impact [16]. Pervious concrete pavements, designed for stormwater management and flood mitigation, often suffer from low mechanical properties due to their highly porous macrostructure. The use of composite materials in pavement reinforcement provides numerous benefits, including high strength-to-weight ratio, corrosion resistance, design flexibility, and extended service life. The incorporation of materials such as crushed brick, recycled crushed aggregate, and reclaimed asphalt pavement in unbound and cement-stabilized pavement base/subbase applications has been explored [17]. Fiber-reinforced polymers offer a promising solution for the rehabilitation and strengthening of existing structures, as well as the construction of new, high-performance infrastructure components [18]. The application of alkali-resistant glass fibers with cement-treated RAP materials enhances the strength-stiffness characteristics [19]. The inclusion of glass fibers in reclaimed pavement reinforcement enhances fracture resistance, especially when exposed to repeated freeze-thaw cycles, indicating a significant improvement in the durability of the material [20].

1.3. Applications in different pavement structures

1.3.1 Flexible Pavements

Flexible pavements, characterized by their layered structure and ability to deform under load, benefit significantly from the incorporation of composite and geosynthetic materials. The implementation of composite and geosynthetic materials in flexible pavements results in improved structural capacity, decreased rutting, increased fatigue resistance, and prolonged service life. The inclusion of fibers such as asbestos, lignite, polyester, polyacrylonitrile, carbon, and brucite fibers improves the viscoelastic properties in asphalt binders [21]. Geosynthetics such as geotextiles and geogrids are strategically placed within the pavement structure to provide reinforcement, separation, filtration, and drainage functions.

1.3.2 Rigid pavements

Rigid pavements, distinguished by their high stiffness and flexural strength, can also benefit from the utilization of composite and geosynthetic materials. The incorporation of fibers into concrete mixtures enhances their flexural strength, impact resistance, and crack control. By incorporating materials like polypropylene fibers, the formation of plastic shrinkage cracks can be reduced, thereby enhancing the durability and longevity of the pavement. The integration of geosynthetics as interlayer systems between the concrete slab and the base course minimizes stress concentrations, prevents reflective cracking, and improves load transfer efficiency [22]. Steel fibers offer more benefits than other types of fibers for the modification of asphalt mixtures, and these fibers contribute to improving the electrical conductivity of the mixtures, which can be useful for the application of thermo- electrical techniques approaching the issue of freeze-thaw cycles on roads, and especially for the self-healing and self-monitoring of pavement structures [21]. The use of waste materials in asphalt mixtures not only promotes sustainability but also enhances the mechanical properties and overall performance of the pavement. The addition of fibers to asphalt mixtures ensures their stability and mechanical strength, reducing penetration and increasing the softening point [21]. Modified asphalt mixtures with plastic polymers can significantly extend the service life of road surfaces [23]. Waste plastic materials can be used as modifier additives with asphalt blends, offering multiple environmental and economic advantages [24]. Recent studies confirm that incorporating nano clay in asphalt is expected to improve the mechanical properties and the service life of the asphalt [25]. The utilization of geosynthetics in overlays can provide an alternative to the removal and replacement of deteriorated rigid pavements [26].

1.3.3 Unpaved Roads

Geosynthetic materials offer a practical solution for reinforcing unpaved roads. Geosynthetics in unpaved roads enhance bearing capacity, reduce rutting, and minimize the required fill thickness [15]. The use of geosynthetics as reinforcement increases lateral restraint or passive resistance of the fill material, increasing the rigidity of the system and reducing vertical and lateral pavement deformations [27]. Geosynthetics are installed between the subgrade and the road to separate or reinforce the structure [15]. Geogrids, in particular, interlock with the aggregate base course, providing confinement and preventing lateral displacement under traffic loads [28]. This interlocking mechanism enhances the load-bearing capacity of the road and reduces the amount of deformation [27].

1.3.4 Airfield pavements

Airfield pavements are subject to heavy loads and high traffic volumes, necessitating robust reinforcement strategies. Airfield pavements must be designed to withstand the impact of aircraft, with landing gear arrangements having a significant effect on pavement design. The use of composite materials in airfield pavements can enhance their structural capacity, fatigue resistance, and durability. The inclusion of high-performance fibers such as carbon fiber or aramid fiber can significantly improve the tensile strength and stiffness of the pavement. Geosynthetics such as geogrids and geotextiles are strategically placed within the pavement structure to provide reinforcement, separation, filtration, and drainage functions [26]. Geosynthetics can prevent reflective cracking, improve load distribution, and enhance the overall performance of airfield pavements. Laboratory tests have shown that geosynthetic reinforcement can reduce pavement thickness by 20–50% [27]. The traffic benefit ratio is a useful metric to measure the improvement to the pavement system that is provided by geosynthetic reinforcement, and it can be directly measured by pavement researchers through laboratory, field, and numerical modeling investigations [5]. The inclusion of geosynthetics resulted in a considerable improvement in rutting, owing to the development of permanent strain in the pavement and soil layers [29]. The reinforcement arrangement with the geosynthetic layer can prevent accidental damage [30].

1.4. Composite and geosynthetic materials for reinforcement

Soil stabilization is a technique employed to enhance the engineering properties of soil, including shear strength, compressibility, density, and hydraulic conductivity [31]. Traditional methods involved soil stabilization and mixing with cementitious binders [32]. When dealing with problematic soils such as expansive clays, traditional methods of soil stabilization may not be sufficient, necessitating the use of more advanced techniques such as geosynthetic reinforcement or chemical stabilization [33]. The use of additives and admixtures, such as lime, cement, oils, bitumen, and chemicals like sulfur, is one of the oldest and most widespread methods of improving a soil [34]. When these stabilizing agents are used, they can improve and maintain soil moisture content, increase soil particle cohesion, and serve as cementing and waterproofing agents [35]. The process of mixing the soil with additional additives is known as the admixture's technique. Soils that do not feature in-demand characteristics for a particular construction can be reinforced by adding one or more stabilizers [36]. Fiber reinforcement can be a viable alternative in projects that involve strengthening thin soil layers and improving local soil. Rapid global population growth has increased socioeconomic demand for the development and expansion of civil infrastructure at an unprecedented rate [37].

Geotextiles are permeable fabrics that, when used in conjunction with soil, have the ability to separate, filter, reinforce, protect, or drain [11]. Geogrids are geosynthetics consisting of polymers, such as polypropylene, polyethylene, or polyester, and are used to reinforce soils and similar materials. Geogrids are frequently employed to reinforce retaining walls, as well as subbases or subsoils beneath roads or structures. Geocells are three-dimensional polymeric structures that can be filled with soil, sand, or aggregate to provide confinement and reinforcement. Geocomposites are materials made by combining geotextiles, geogrids, geomembranes, and/or geonets. The use of geosynthetics as soil reinforcement has become an increasingly popular and effective method for improving the performance and stability of soil structures. The use of geosynthetic reinforcement in base layers leads to increased stiffness, reduced permanent deformation, and improved load distribution [38]. The capacity of soil stabilization to improve the physical qualities of soil, such as bearing capacity and increased shear strength, which are regulated by specific factors such as the addition of appropriate admixtures or compaction such as lime, cement, fly ash, and phosphogypsum [39].

1.5. Geosynthetic applications in various pavement structures

The selection of appropriate geosynthetic materials and installation techniques depends on project-specific factors, including soil type, traffic loading, environmental conditions, and performance requirements. Geosynthetics have been effectively employed in pavement systems to enhance structural capacity, extend service life, and reduce maintenance costs [10]. The use of geosynthetics in pavement reinforcement applications has been shown to improve performance, reduce maintenance, and extend service life. Geosynthetics are frequently utilized in the construction of reinforced soil walls and slopes, where they provide tensile reinforcement to the soil mass and enhance stability [1]. Geosynthetics have been effectively employed in the construction of reinforced soil walls and slopes, where they provide tensile reinforcement to the soil mass and enhance stability [12]. Geosynthetics such as H2Rx, Geogrid, Geotextile, and Geomembrane were selected for reinforcing the pavement layer due to their proven effectiveness [10]. Laboratory tests, field studies, and numerical modeling have been used to evaluate the performance of geosynthetic-reinforced pavement systems under various loading and environmental conditions [10].

Geosynthetics are also utilized in subsurface drainage systems to filter and collect water, thereby preventing clogging and maintaining drainage efficiency. Geosynthetic-reinforced soil offers economy, ease of installation, performance, and reliability in many areas of geotechnical engineering, e.g., construction of footings over soft soil, stable embankments, slope and earth stabilization, road construction layers, and pavement systemss [38]. Additionally, stabilization of expansive soils is achieved through improvements in compressive strength, permeability, plasticity, compressibility, and durability [40]. In regions with soft subgrades, geosynthetics have been employed to improve the bearing capacity and reduce deformation of the pavement structure [9]. The inclusion of coir geotextiles enhanced the bearing capacity of thin sections, and the placement of geotextiles at the interface of the subgrade and base course increased the load-carrying capacity significantly at large deformations [41]. The capacity of soil stabilization to improve the physical qualities of soil, such as bearing capacity and increased shear strength, which are regulated by specific factors such as the addition of appropriate admixtures or compaction, such as lime, cement, fly ash, and phosphogypsum.

The cyclic plate load test is widely used to evaluate the performance of geosynthetic reinforced pavements because it is inexpensive and saves time [7]. The results of cyclic plate load tests conducted on pavement prototypes indicate that geosynthetic reinforcement can significantly reduce permanent deformation and improve the traffic improvement ratio, suggesting enhanced performance and durability [9]. In the context of road construction over soft subgrades, construction alternatives such as industrial by-products and geosynthetics offer potential benefits. The implementation of geosynthetics leads to an increase in the resilient modulus of the base course layer by approximately 25% and reduces the base layer thickness by about one-third for pavement sections with a 457 mm thick base and a single layer of geosynthetic [7]. Moreover, the ability to utilize industrial by-products like foundry slag, foundry sand, bottom ash, and fly ash as subbase layer materials not only reduces construction costs but also promotes sustainable waste management practices [42]. The utilization of woven coir geotextiles demonstrates superior performance compared to hand-knotted coir nettings [14].

The geosynthetic reinforcement not only improves the performance of pavement structures but also reduces the required thickness of base layers [9]. Geosynthetics have been found to effectively enhance the rutting performance of pavement [43]. The placement of geosynthetic reinforcement within pavement structures can lead to a substantial reduction in rut depth, indicating improved resistance to permanent deformation under traffic loading [9]. This improvement is attributed to the ability of the geosynthetic material to provide tensile reinforcement and lateral confinement to the base or subgrade layers, thereby enhancing their load-bearing capacity and reducing the development of rutting [9]. Overall, the selection and application of geosynthetic materials in pavement structures require careful consideration of site-specific conditions, loading requirements, and performance objectives [13]. Moreover, recycled materials, such as recycled glass, can be integrated into pavement base layers, offering a sustainable alternative to virgin aggregates [44]. The type of geosynthetics used influences the performance of geosynthetic reinforcement [9].

The use of reclaimed asphalt pavement materials in road construction has been proven to reduce both the amount of construction debris disposed of in urban landfills and the rate of depletion of natural resources [19]. Geosynthetic reinforcement enhances pavement performance through the tension membrane effect and lateral confinement, dispersing loads and mitigating stress on the subgrade [9]. The incorporation of geosynthetics serves to improve tensile strength and stiffness within the pavement structure, consequently diminishing the tensile strain experienced at the base of the asphalt layer. This, in turn, mitigates the propagation of cracks within the pavement, thereby prolonging its overall service life. The correct placement of geosynthetic is critical for performance improvement. Studies indicate that the placement of geosynthetics at the interface between the asphalt layer and the subgrade results in improved pavement performance [26]. Also, placing geosynthetics above a weak subgrade can help prevent reflective cracking [27].

The application of polymer-modified asphalt mixtures has emerged as a prominent strategy for enhancing the performance and durability of road pavements [24]. The incorporation of waste polymer components into stone mastic asphalt mixtures has demonstrated improvements in indirect tensile strength, Marshall stability, moisture damage resistance, and resistance to permanent deformation [45]. The utilization of recycled polymer-modified mixes exhibits the highest resistance to rutting, as evidenced by repeated load axial creep tests [45]. The performance of asphalt pavements is significantly influenced by the characteristics and composition of the asphalt binder [46]. To meet the escalating demands for high-performance pavements, researchers have explored the incorporation of polymers into asphalt binders through mechanical mixing or chemical reactions [47]. The use of geopolymer binders could also be a good choice, as they produce fewer greenhouse gases compared to cement [16].

The modification of bitumen and asphalt mixes with additives, including plastic polymers, is one method of extending the service life of road surfaces [23]. The utilization of nanoclay in asphalt mixtures is expected to improve mechanical properties and extend the service life of the pavement [25]. The inclusion of waste plastic materials into bituminous mixes has been found to enhance the strength and performance of pavements [48]. The incorporation of recycled asphalt pavement aggregates into geopolymer matrices has demonstrated promising results in producing paver blocks of desirable quality [49]. The increasing volume of traffic, axle load, and overloading, coupled with environmental factors, frequently leads to cracking in asphalt pavement. The effectiveness of reinforcement in mitigating crack propagation depends on factors such as the type of existing surface layer and the positioning of the geogrid. Incorporating waste PET as an additive in road paving mixtures could improve the overall quality of roads and also be a sustainable waste disposal option [50].

1.6. Reinforcement of subgrade and base layers

The ability of composite and geosynthetic materials to improve the mechanical qualities of soil and base layers is the focus of this study's bibliometric analysis. This study attempts to offer a thorough summary of the existing research landscape and possible directions for future investigation by analyzing the trends, crucial players, and significant publications in this field. Pavement engineering is seeing increased use of geosynthetic materials to improve structural integrity and lengthen service life. Using these materials aligns with sustainability in the pavement industry, especially when paired with low-quality materials. Geosynthetics such as geogrids and geotextiles can improve the performance of pavements with weak subgrades by improving load distribution and reducing stress concentration, thus reducing deformation and failure.

The use of composite materials, which combine two or more materials with different physical and chemical properties, has also emerged as a promising strategy for reinforcing subgrades and base layers. Fiber-reinforced polymers, which have a high strength-to-weight ratio and corrosion resistance, are frequently used in pavement applications to improve the strength and durability of base layers. The use of recycled concrete aggregate in the construction of pavement is a suitable substitute since roads usually need a tremendous volume of crushed aggregates [51]. The use of geosynthetic materials, such as geogrids and geotextiles, offers a compelling approach to enhance the structural capacity and longevity of pavement systems [9]. The primary functions of geosynthetics in pavement applications include reinforcement, separation, filtration, drainage, and containment.

Pervious concrete has become increasingly popular as an environmentally beneficial option for urban areas due to its capacity to manage stormwater runoff and reduce the heat island effect [52]. The usage of geosynthetic materials with pervious concrete pavements can further enhance their performance and durability [6]. The incorporation of geosynthetics, such as geotextiles or geogrids, within the pervious concrete structure can improve its structural integrity, prevent clogging, and extend its service life. The use of geosynthetic materials, such as geogrids and geotextiles, offers a compelling approach to enhance the structural capacity and longevity of pavement systems. The primary functions of geosynthetics in pavement applications include reinforcement, separation, filtration, drainage, and containment.

Pervious concrete's highly porous macrostructure causes it to have lower mechanical qualities than regular Portland cement concrete. Recycled carbon fiber composite material can be used as discrete structural reinforcement in a pervious concrete pavement demonstration project [53]. The structural characteristics of the pavement and its lifespan are enhanced by the inclusion of recycled carbon fiber composite. In recent years, the use of nanoclay has received interest in order to enhance the properties of construction materials, which can also be eligible for pavement technology and engineering applications [54]. By creating nanocrystals, filling pores and microcracks, and densifying the microstructure, nanotechnology considerably improves the efficiency of concrete structures [55]. Because of their pozzolanic qualities, nanoclays, particularly nMt, have the capacity to eliminate organic pollutants [56].

The reinforcement layer increases the fill material's lateral restraint or passive resistance, which raises the system's stiffness and decreases vertical and lateral pavement deformations [27]. The resilient modulus of road foundation materials, base materials, and subbase materials is significantly increased by geogrid reinforcement. When geosynthetic reinforcement is added, pavement systems' permanent deformation behavior is greatly enhanced. The use of both geogrid and geotextile products has shown that the geogrid products used were superior to the geotextile products chosen [57]. The improvement to the pavement system provided by geosynthetic reinforcement can be directly measured by a traffic benefit ratio, which is defined as the ratio of the number of load cycles on a reinforced section to reach a defined failure state to the number of load cycles on an unreinforced section, with the same geometry and material constituents, to reach the same defined failure state [5]. The geosynthetics can be easily installed after the subgrade is ready; however, rehabilitation can be difficult. The use of fiber-reinforced polymers, which have a high strength-to-weight ratio and corrosion resistance, is frequently used in pavement applications to improve the strength and durability of base layers.

The growing number of vehicles with heavier wheel loads, along with increased traffic volumes and fluctuating weather conditions, increases road stresses and strains, which can lead to pavement degradation in the form of cracking, rutting, stripping, and fatigue [25]. The incorporation of nanomaterials into concrete composites has proven to be a very effective technique to improve concrete properties by enhancing the formation of hydration products [58]. Nanomaterials also have the potential to change the characteristics of soil [59]. The method improves the soil's qualities by reducing the amount of void space, which in turn lowers permeability and increases strength and durability. The use of waste plastic material as modifier additives with asphalt blended may have multiple environmental and economic advantages [24]. Using waste plastic in pavement construction offers cost savings, lowers plastic garbage, and may increase pavement performance [5]. Asphalt pavements are subjected to loads during their service life in conjunction with harsh environmental conditions and the increasing environmental requirements of highway network usage, all of which contribute to pavement deterioration and poor performance, reducing its service life [46].

The incorporation of fibers into hot-mix asphalt pavements has emerged as a viable strategy for enhancing their performance characteristics [20]. The inclusion of cup lumps rubber as a modifier to modified binder has been shown to improve the properties of the binder and, consequently, the performance of asphalt mixes [60]. The use of cellulose-reinforced and end-of-life tire fiber-reinforced hot mix asphalt mixtures was found to have superior performance when compared to standard hot mix asphalt mixtures [61]. In order to address the key flexible pavement issues of rutting, fatigue cracking, thermal cracking, and raveling, a considerable number of fiber-modified asphalt binders and fiber-modified asphalt mixtures have been developed [21]. Adding fibers to the binder or bituminous mixtures ensures their stability and mechanical strength [21]. Fibers have been used to improve the performance of Portland cement concrete by increasing its modulus, resistance, durability, and deformation capacity [21]. The addition of fine carbon fiber composite materials and synthetic fibers reduced the porosity and infiltration rate, while both fibers prevented draindown of asphalt binder at an elevated temperature [62]. Fibers can reinforce the asphalt mastic through the generation of a three-dimensional network, thus improving the mix adhesion [21]. Tensile strength, permanent deformation, and moisture susceptibility have also been improved [21].

Waste-plastic-modified bitumen has been shown to enhance rutting and fatigue resistance [23]. The use of waste fibers from industrial processes in fiber-reinforced asphalt mixes can provide a sustainable solution, but it is essential to consider the compatibility of these fibers with the asphalt matrix and their long-term performance under varying environmental conditions [21]. The performance of fiber-modified asphalt mixtures is influenced not only by the optimum fiber content but also by the fiber length, which affects the mixture's overall performance [21]. According to research, shorter fibers disperse more effectively than longer ones when studying the impact of polypropylene fiber length on fiber dispersion within modified mixtures [20]. The utilization of recycled polymer components has been shown to enhance the indirect tensile strength, Marshall stability, moisture damage resistance, and resistance to permanent deformation of stone mastic asphalt mixtures [45]. The addition of fibers can improve the high-temperature performance and moisture susceptibility of asphalt mixtures. Waste plastic is the best modifier. It makes a plastic layer on the surface of the aggregate and thus reduces porosity and water absorption and also improves binding properties of bitumen [48].

The mechanical behavior of asphalt concrete is intrinsically linked to the bitumen used, with its response being highly temperature-dependent [21]. In order to overcome this challenge, researchers have explored various modifiers, including polymers, to enhance the performance of asphalt binders. Various polymers, such as styrene-butadiene-styrene, styrene-butadiene rubber, and polyethylene, have been used to modify the base asphalt in order to improve the performance of road pavement [47]. Using reclaimed asphalt pavement and polyethylene terephthalate to modify the bitumen binder can improve the properties and chemical compatibility of the bitumen binder [63]. Because polymer modification of asphalt results in improved physical properties of the binder, the resulting mixtures can withstand increased loading and extreme weather conditions, thereby enhancing pavement life. Mixes using polymer-modified asphalt or those treated with hydrated lime increase the mixture's resistance to moisture damage, raveling, and rutting [64]. Polypropylene waste has been shown to improve the characteristics of asphalt mixtures, with a 9% concentration found to be the most effective for enhancing bulk density and flow values [65]. The optimum asphalt content of a mixture increases when polyacrylonitrile is added, and it also has a positive effect on plastic deformations [21].

The incorporation of glass fibers into reclaimed pavements enhances fracture resistance under freeze–thaw cycles, while polypropylene fibers have demonstrated high efficacy in enhancing the durability of bituminous binders and mixtures [20]. The use of polyester fibers in conjunction with lower contents of binder enables the increase of resistance to fatigue and plastic deformation, transferring the force from the mineral structure to the fiber-reinforced mastic [21]. The European Asphalt Pavement Association reported that Europe and the United States produced 265.4 and 319 million tons of asphalt mixtures in 2014, underscoring the importance of improving the mechanical properties and functionality of these mixtures through the addition of fibers [21]. When selecting a modifier, it is essential to consider the local climate and traffic conditions in order to determine its effectiveness. The addition of glass and cellulose fibers decreases the penetration value of bitumen and increases the softening point and viscosity of bitumen [21]. However, both modifiers have been shown to improve the thermal properties of asphalt binder. The addition of brucite fibers would result in better rutting resistance by preventing high-temperature creep of pavements under traffic loads [21].

The Marshall method of mix design has been used to assess the effect of calcium carbide waste on the mechanical properties of hot mix asphalt [66]. The optimum asphalt content increases with the addition of polyacrylonitrile, and it has a positive effect on plastic deformations. The addition of 0.4% nanofiber by weight of mixture results in higher resistance to permanent deformation, resilient modulus, and fatigue life [21]. The fracture energy and toughness of asphalt mixtures can be increased by adding fibers [21]. Aramid fibers have also been shown to be effective in increasing the tensile strength and fatigue life of asphalt mixtures. Using carbon fiber geogrids at the bottom of overlays can effectively delay crack propagation [67]. Fine carbon fiber composite materials premixed with liquid asphalt binder performed the best to reinforce porous hot mix asphalt in terms of indirect tensile strength and cracking resistance [62]. Lignin and polyester fibers have been shown to improve the cracking resistance of high-content SBS-polymer-modified asphalt mixtures, particularly after short-term and long-term aging [67].

The impact of fiber reinforcement on hot mix asphalt is significantly influenced by several factors, including fiber dosage, length, type, and mixing procedures [20]. Fiber-reinforced asphalt mixes exhibit enhanced mechanical characteristics. The optimal fiber content varies based on the specific type of fiber and the desired performance characteristics of the mix. For instance, a 1% reinforcement dosage of both polypropylene fibers and glass fibers is deemed optimal for enhancing performance across various applications, improving the flexibility and crack resistance of hot-mix asphalt [20]. However, exceeding the 1% dosage of polypropylene fibers can lead to reduced crack resistance and increased brittleness [20]. When using fibers in hot mix asphalt, it is important to consider their elongation properties, as low elongation fibers may break during mixing and compaction, while high elongation fibers may not provide sufficient reinforcement [21].

The enhancement mechanism of superabsorbent polymers and basalt fibers on concrete performance has been analyzed, revealing that their combination, which provides internal curing and bridging effects, is beneficial for the crack resistance and service life of concrete pavement [68]. The use of steel fibers offers advantages over other types of fibers for the modification of asphalt mixtures, improving electrical conductivity for thermo-electrical techniques addressing freeze-thaw cycles and enabling self-healing and self-monitoring of pavement structures [21]. The addition of fibers significantly decreases the phase angle in the dynamic shear rheometer test, providing the mastic with a more elastic and less viscous performance. The use of waste polypropylene as a modifier can improve the characteristics of asphalt binder and mixture [69]. The inclusion of steel fiber generally increases the flexibility of concrete [18]. The performance of semi-flexible pavement materials is influenced by the properties of both the cement mortar and the asphalt skeleton, with the water-cement ratio and sand-cement ratio in the cement mortar affecting workability, mechanical strength, and pore structure.

1.7. Synthesis of existing approaches

Geosynthetic reinforcement represents a significant advancement in pavement engineering, offering a cost-effective and sustainable solution for improving the performance and extending the lifespan of roadways [5]. The implementation of recycled materials, such as recycled high-density polyethylene strips, has been proven effective in stabilizing tensile crack propagation within brittle cementitious matrices, highlighting the potential for sustainable and cost-effective pavement solutions [8]. The benefits of geosynthetic reinforcement include increased load-bearing capacity, reduced rutting, and improved resistance to fatigue cracking [26]. These improvements lead to lower maintenance needs and extended pavement life, ultimately reducing lifecycle expenses. The use of reclaimed asphalt pavement materials in road construction reduces construction debris disposed of in landfills and the rate of depletion of natural resources [19]. The results of the laboratory study show that recycled asphalt pavement aggregates can be introduced into a geopolymer matrix to produce paver blocks of desirable quality [49].

Geosynthetics, particularly geocells, have demonstrated effectiveness in reinforcing reclaimed asphalt pavement bases, providing structural support and stability to pavement layers [22]. The inclusion of geogrid reinforcement can significantly decrease permanent deformation and enhance the bearing capacity of pavements constructed over weak subgrades. Moreover, the application of geosynthetics in pavement overlays is a common practice to mitigate crack propagation caused by repeated traffic loads and temperature fluctuations. The inclusion of materials such as fly ash-based geopolymer and reclaimed asphalt pavements can improve the mechanical properties of soil for road base and subbase layers, offering a sustainable alternative to traditional stabilization methods [16]. Sustainable development goals also involve industries and infrastructures, aiming to increase resource-use efficiency and greater adoption of clean and environmentally sound technologies to achieve a more sustainable future [70].

The application of waste polymer components has been shown to increase the indirect tensile strength, Marshall Stability, moisture damage resistance, and resistance for permanent deformation of stone mastic asphalt mixtures [45]. Utilizing waste materials in pavement construction enhances asphalt qualities while also resulting in considerable savings in road material expenses, assisting in resolving disposal issues for such waste materials, which are frequently hazardous because they can cause water, soil, and air pollution [69]. The incorporation of waste materials as a substitute for virgin materials in road construction aligns with sustainable practices by reducing environmental impact and promoting resource conservation [23]. The utilization of RAP as a base course material may lead to excessive deformation under traffic loading due to the presence of asphalt. However, geocell reinforcement has been proposed to minimize deformation by confining the RAP material [28]. The adoption of sustainable and cost-effective mechanical stabilizers like geocells can enhance the utilization and performance of RAP base materials [22].

Geosynthetic materials are increasingly employed in pavement construction to enhance structural integrity and extend service life [28]. The use of geosynthetics contributes to sustainability in the pavement industry, particularly when combined with marginal materials [9]. The inclusion of geosynthetics in pavement structures can significantly improve performance and extend service life by effectively managing stress distribution and minimizing deformation [26]. Geosynthetics offer a versatile solution for addressing various challenges in pavement engineering, including weak subgrades, reflective cracking, and moisture damage. Using geosynthetics to reinforce base layers allows for the successful use of marginal materials, improving overall pavement performance. Geogrids and geocells are the geosynthetic materials often used to improve the strength and performance of pavement layers [43]. They function by providing confinement and support to the aggregate material, increasing its load-bearing capacity and resistance to deformation.

The cost-effectiveness and environmental benefits of using geosynthetics and composite materials have made them essential to modern pavement engineering, as they enable more sustainable and resilient infrastructure. The use of reclaimed asphalt pavement is a useful alternative to virgin materials because it reduces the need to use virgin aggregate, which is a scarce commodity in some areas of the United States [71]. More than 76.9 million tons of reclaimed asphalt pavement were utilized in the United States, according to Hansen and Copeland [22]. The study aimed to assess how well geocell reinforcement worked on RAP base courses. To ascertain the structural support offered by geocell reinforcement, a series of large-scale repeated load box tests were carried out on unreinforced RAP base sections and geocell-reinforced RAP base sections. The RAP sections were shown to widen the stress distribution angle and reduce the rut depth if the base courses were compacted equally in unreinforced and reinforced sections [28]. The use of high-density polyethylene geocell increased the base layer's resilient modulus by 2.5 to 3.3 times and decreased the permanent deformation of the RAP base by 70 to 80% for GRRB of 200 mm thickness [22]. Moreover, incorporating RAP aligns with sustainable practices, reducing environmental impact and promoting resource conservation [72-73]. Also, the performance of the base layer may be affected if clay particles contaminate the RAP base by lowering the resilient modulus.

The utilization of reclaimed asphalt pavement presents an appealing avenue for cost reduction, waste minimization, and environmental preservation [74]. The incorporation of RAP into pavement construction not only reduces the demand for virgin materials but also alleviates landfill congestion by diverting asphalt waste from disposal sites [75]. RAP consists of high-quality and well-graded aggregates coated by bituminous mastic [76]. RAP is frequently used in the construction of base courses, subbases, and embankments. The rise in RAP applications highlights environmental concerns, especially those pertaining to the exploitation of natural resources. To maximize RAP's potential, research into its properties is essential [77]. For effective recycling, the material needs to be treated as a secondary raw material and processed. The addition of a rejuvenator can significantly improve the low-temperature performance and moisture susceptibility of recycled asphalt mixtures, especially for AC-20 ordinary recycled asphalt mixture [78]. RAP mixes can produce results that are comparable to, or even better than, virgin mixes, making RAP use advantageous. The use of geocells as reinforcement to impart confinement to the RAP material can reduce the effect of contamination of the RAP base by clay particles [22].

1.8. Gaps in the literature

Despite the advancements in utilizing composite and geosynthetic materials for reinforcing subgrades and base layers, there remain notable gaps in the existing literature that warrant further investigation. One such gap pertains to the comprehensive understanding of the long-term performance and durability of pavements reinforced with composite and geosynthetic materials under varying environmental conditions and traffic loading scenarios [64]. While laboratory studies and accelerated pavement testing have provided valuable insights into the short-term performance of reinforced pavements, there is a need for long-term field studies to assess their performance over extended periods. It's also important to analyse the environmental and life cycle costs of these materials in road construction.

Moreover, there is a lack of standardized testing protocols and design guidelines for incorporating composite and geosynthetic materials into pavement structures, which hinders their widespread adoption and implementation. The absence of standardized testing methods makes it challenging to compare the performance of different materials and designs, while the lack of design guidelines makes it difficult for engineers to select the appropriate materials and configurations for specific pavement applications. Further research is also needed to explore the use of sustainable and environmentally friendly materials in pavement reinforcement, such as recycled plastics, reclaimed asphalt pavement, and bio-based polymers.

Furthermore, the existing literature predominantly focuses on the mechanical performance of reinforced pavements, with limited attention given to other critical aspects such as skid resistance, noise reduction, and water drainage. These factors play a significant role in ensuring the safety, comfort, and functionality of pavements, and their integration into the design and evaluation of reinforced pavements is essential. Additionally, the studies have shown that the optimal design of reinforced pavements depends on factors such as geosynthetic type, manufacturing process, mechanical properties, placement location, and layering; base course thickness and quality; asphalt concrete thickness; subgrade type, strength, and drainage; traffic volume and loading; and environmental conditions.

Finite element models provide an efficient and cost-effective means to analyse the structural behaviour of pavement systems incorporating geosynthetic reinforcement [5]. A series of finite element simulations can be carried out to evaluate the benefits of integrating a high-modulus geosynthetic into the pavement foundation [5]. These models have demonstrated reasonable accuracy, with discrepancies potentially arising from factors such as construction quality, material variability, and simplification of boundary conditions. It is also important to look into using recycled materials and industrial by-products in road construction for both sustainability and economic benefits.

1.9. Bibliometric analysis

Bibliometric analysis is a quantitative research method used to analyse and measure the impact of publications, authors, and research topics. It utilizes mathematical and statistical methods to analyse trends, patterns, and relationships within a body of literature. Bibliometric methods are valuable tools for understanding the structure and evolution of scientific disciplines, identifying key research areas, and assessing the impact of publications and authors [79]. Bibliometric analysis employs various techniques, including citation analysis, co-citation analysis, bibliographic coupling, and co-word analysis, to map the relationships between publications and identify research trends [80].

Bibliometric analysis plays a crucial role in identifying emerging trends, research gaps, and influential publications within a specific field [81]. By analysing citation patterns, researchers can identify highly cited articles and journals, which are indicative of significant contributions to the field [21,81]. Bibliometric studies can also reveal the intellectual structure of a research area by identifying clusters of co-cited articles that share common themes or methodologies. Moreover, bibliometric analysis facilitates the assessment of research impact by quantifying the number of citations, publications, and collaborations associated with specific authors, institutions, or countries. The development of the internet has facilitated communication and access to contributions, leading to exponential growth in bibliometric methodologies [82].

The methodology involves several key steps, starting with defining the scope of the research and selecting relevant databases such as Web of Science, Scopus, and Google Scholar to extract publication data [83]. Search queries are formulated to retrieve publications based on keywords, authors, affiliations, or publication dates. The extracted data is then cleaned and pre-processed to remove duplicates and standardize information. Bibliometric analysis is considered a recognizable method of quantitative analysis for scientific papers [84]. The cleaned data is analysed using various bibliometric indicators, such as publication counts, citation counts, co-citation analysis, keyword analysis, and network analysis, to identify trends, patterns, and relationships within the literature. Visualizations, such as network maps and trend graphs, are created to present the findings in an accessible format [85].

Bibliometric analysis provides quantitative insights into research trends, influential publications, and collaboration patterns, complementing qualitative reviews and expert opinions. Bibliometric data, which includes publication information from online databases, serves as big data for evaluating research quality and performance internationally [86]. It has become a popular method of providing insight into research in specific fields [87]. Bibliometric analysis can evaluate the performance of disciplines, journals, authors, institutions, and countries and assess co-authorship patterns [88]. Interplay is vital between those involved in refining bibliometric methods and the recipients of this type of analysis [89]. Despite its strengths, bibliometric analysis has limitations, including biases in data sources, the potential for misinterpretations of citation patterns, and the exclusion of non-indexed publications [90]. It is important to use bibliometric methods in conjunction with qualitative assessments and expert judgment to obtain a comprehensive understanding of the research landscape [80,91-93].

2. Material and Method

A combination of citation analysis, co-authorship patterns, and keyword co-occurrence was utilized to identify the most influential publications, key research topics, and emerging trends in the field of reinforcement of subgrade and base layers with composite and geosynthetic materials for pavement applications, including highways, airfields, and railways.

An important database, such as Web of Science, was searched using keywords related to the reinforcement of subgrade and base layers with composite and geosynthetic materials for pavement applications, including highways, airfields, and railways. The citation patterns of the retrieved publications were analyzed to identify the most influential works in the field. Additionally, the co-authorship networks were examined to uncover the collaborative dynamics among researchers, as well as the keyword co-occurrence to map the thematic structure of the research.

This bibliometric analysis was carried out on February 15, 2025, examining publications spanning the years 1986-2025 and utilizing the Web of Science database as the data source. The search parameters yielded a sample dataset comprising 6050 articles, which were the subject of the study (data retrieved from http://apps.webofknowledge.com on 15.02.2025).

The bibliometric analysis method was adopted in the study, and the VOSviewer program was used to examine the publications. The key results presented include the publication year distribution, the most frequently used keywords, the country with the most publications, the researcher with the most publications, the researcher with the most co-authorships, the country with the most citations, and the researcher with the most citations, all for the 6050 publications examined. In addition, visual analysis was performed by creating network maps, and the obtained findings were discussed in detail to provide a comprehensive overview of the research trends and dynamics in the field.

2.1. VOSviewer

VOSviewer is a software tool employed for constructing and visualizing bibliometric networks [94]. These networks may include journals, researchers, or individual publications, and they are constructed based on co-citation, bibliographic coupling, co-authorship, or co-occurrence [95]. VOSviewer also offers text mining functionality, enabling the extraction of terms from scientific literature for the construction and visualization of term maps. VOSviewer is valuable in the analysis of bibliometric data, displayed visually through mapping tools, which is essential in the current era of rapid technological advancement [96].

3. Results and Discussion

In the visualization provided by VOSviewer, each circle represents an item, such as a publication, author, journal, or keyword, that is selected according to the filtering criteria determined by the researcher [97]. These items are displayed as nodes within the network map, and the connections between them, such as co-citations, co-authorships, or co-occurrences, are represented by the lines linking the nodes [98]. The size and position of the nodes within the network reflect the relative importance or influence of the corresponding items, providing a visual representation of the research landscape and its underlying structure. Bibliometric maps displayed through VOSviewer can be adjusted using features such as zooming, scrolling, and searching [96].

The size of the nodes reflects the relative frequency of occurrence for the corresponding items; the largest nodes represent the most prevalent elements. The items are color-coded and organized into clusters based on their occurrence scores [99]. While each item can only belong to one cluster, it's also possible for some items not to be assigned to any cluster. Some items may not be strongly associated with a particular group, or the clustering algorithm may not be able to confidently place them within a specific cluster based on the data and parameters used.

The flexibility to have unassigned items allows the visualization to more accurately represent the complexity and nuances of the research landscape, capturing both well-defined thematic areas as well as unique or isolated elements that do not readily fit into the dominant clusters [100]. The connections between the items are depicted by the lines, where the line thickness reflects the strength of the relationships. Thinner lines indicate weaker connections, whereas thicker lines signify stronger connections [101]. This visualization method offered by VOSviewer provides a valuable tool for researchers to deeply understand the complex structure, interconnections, and underlying dynamics within the scientific research landscape. The flexibility of the software to visualize various bibliometric networks, such as co-citations, co-authorships, and keyword co-occurrences, allows for a comprehensive analysis of the research field. This type of visual analysis is particularly insightful in rapidly evolving areas, as it can help identify key players, emerging trends, and influential research directions to guide future studies [94,102].

VOSviewer is a software tool widely employed in bibliometric studies, enabling researchers to visually map research areas, uncover trends, and identify influential actors within a field of study [103]. This type of bibliometric analysis and visual mapping using tools like VOSviewer is particularly valuable in rapidly evolving fields, such as digital learning, for comprehensively evaluating research performance, identifying key players and influential works, and setting strategic directions for future studies in the field. The flexibility of these visualization tools allows researchers to gain deeper insights into the complex structure, interconnections, and underlying dynamics within a research landscape, which is crucial for guiding the development of emerging areas like digital learning [104- 106].

3.1. Keyword analysis

Figure 1 illustrates the keywords used in publications on "(pavement or railway) and (composite* or geosynthetic)" indexed in Web of Science. From a total of 16027 keywords, 301 were selected based on a minimum frequency of ten occurrences. The most frequent keyword is "mechanical properties" (171 occurrences), followed by "geosynthetics" (167 occurrences). Other prominent keywords include "microstructure," "asphalt," "asphalt mixture," "pavement," "rheological properties," "bitumen," "durability," "concrete," "compressive strength," "fatigue," "rheology," "asphalt binder," "asphalt concrete," "asphalt pavement," "finite element analysis," "composite," "road engineering," "rutting," "geogrid," "reclaimed asphalt pavement," and "recycling."

This visualization, generated using VOSviewer, maps the most frequent keywords in publications on these topics. The size of the circles representing the keywords in the visualization is proportional to the frequency of their occurrence, with larger circles indicating more frequently used keywords. The proximity of keywords to each other indicates the strength of their co-occurrence, with closer proximity indicating stronger associations. In bibliometric analysis, keywords are crucial as they highlight and characterize the main topic of the research domain.

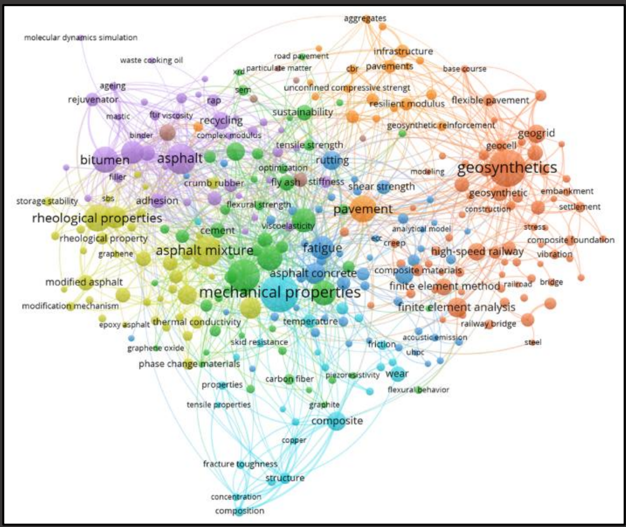

Figure 1. Keyword analysis

The graph shown in Figure 1 displays clusters of keywords in various colors, each representing distinct thematic focuses within the research field. For example, the cluster containing "asphalt mixture," "mechanical properties," and "rheological properties" indicates a research emphasis on the material characteristics and performance of asphalt mixtures, reflecting a focus on understanding the mechanical and rheological properties of these construction materials. The interconnection and co-occurrence of these keywords suggest that studies in this cluster often investigate the relationship between the composition, structure, and performance of asphalt mixtures, providing insights into their suitability for different pavement applications.

Keywords such as "pavement," "composite," and "geosynthetics" are located at the central region of the visualization. This centrality signifies their pivotal role in the research domain, as they represent key concepts that are strongly connected to and frequently co-occur with other prominent keywords in the field. These central keywords serve as crucial hubs, highlighting the fundamental importance of pavement engineering, composite materials, and geosynthetics within the overall research landscape depicted in the bibliometric map.

The lines connecting keywords in the visualization represent the frequency of their co-occurrence in research articles, indicating the strength of the relationships between them. For instance, the robust link between the keywords "geogrid" and "geocell" suggests that these two concepts are frequently considered together in pavement engineering applications, highlighting their close association and joint relevance within the research field.

The visualization also provides insights into current research trends. The presence of keywords like "sustainability" and "recycling" highlights the growing interest in environmentally friendly pavement materials and methods, such as the development and utilization of recycled and eco-friendly construction materials for pavement applications. This trend reflects the increasing emphasis on sustainable practices and the desire to minimize the environmental impact of pavement construction and maintenance.

3.2. Most co-authorship analysis

Figure 2 presents the researchers with the most co-authorships. A total of 17,861 researchers were identified in the publications analysed. Of these researchers, 149 were selected for further analysis based on meeting the criteria of having published at least 8 papers and having received a minimum of 5 citations. This subset of 149 researchers was considered for the co-authorship analysis to identify the key collaborative relationships and influential scholars within the research field.

Examining the Figure 2, it can be seen that the researcher with the most co-authorships is Yuan, Qiang, who has established extensive collaborative relationships within the research field. This prolific researcher is followed by a group of other prominent co-authors, including Mechnik, V. A., Kolodnitskyi, V. M., Bondarenko, N. A., Gevorkyan, E. S., Ratov, B. T., Gong, Minghui, Pei, Jianzhong, and Wu, Shaopeng, each of whom has also demonstrated a significant level of collaborative engagement as evidenced by their positioning in the order of co-authorships.

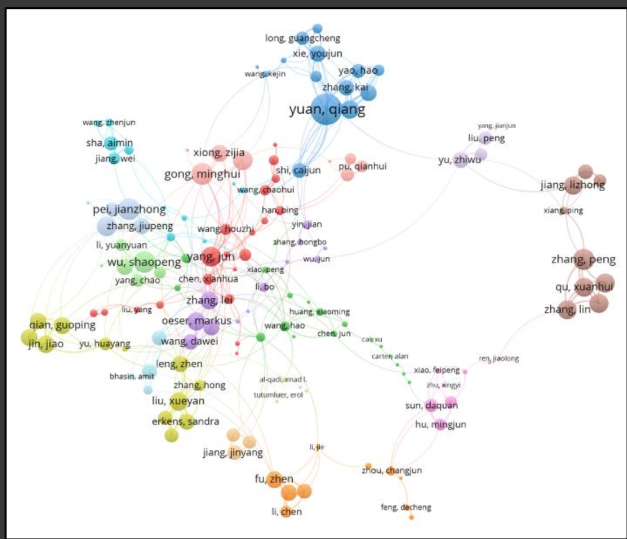

Figure 2. Researchers with the most co-authorships.

The graph shown in Figure 2 displays authors clustered in various colors, each representing distinct collaborative groups within the research field. Authors within the same cluster demonstrate a higher frequency of co-publication and closer collaboration, indicating the existence of research teams or groups that frequently work together on joint projects and publications. These collaborative clusters provide insights into the social structure and knowledge-sharing networks that underlie the research landscape.

The positioning of researchers like "Yuan, Qiang," "Pei, Jianzhong," "Wu, Shaopeng," and "Yang, Jun" in the central regions of the graph reflects their pivotal roles and extensive collaborative networks within the research domain. These central authors have established themselves as hubs of collaboration, indicating their significance and influence in shaping the research landscape through their numerous co-authorship relationships and joint publications with other prominent scholars in the field.

The connecting lines between authors in the graph represent the frequency of their co-authored publications, signifying the strength and intensity of their collaborative relationships. For instance, the robust link between the researchers "Shi, Caijun" and "Gong, Minghui" indicates their frequent and extensive collaboration within the research area, highlighting the close working partnership they have established through their joint publications and scholarly activities.

The graph also provides insights into collaboration trends within the research field. Densely clustered groups of authors suggest the prevalence of interdisciplinary or multi-institutional collaborations, where researchers from diverse backgrounds or affiliated with different centers and universities work together on joint projects and publications. This clustering pattern indicates a collaborative research environment that fosters cross-disciplinary knowledge exchange and the integration of complementary expertise, which can lead to more innovative and impactful research outcomes.

3.3. Analysis of countries with the most publications.

The network visualization depicted in Figure 3 is the output of a "countries with the most publications" analysis conducted using the VOSviewer bibliometric software. This analysis was performed on data retrieved from the Web of Science database, focusing on publications that included the keywords "pavement," "composite," and "geosynthetics." The network map illustrates the countries with the highest research output in these areas and the collaborative relationships between them. Each country is represented as a node, and the lines connecting the nodes indicate the number of co-authored publications, reflecting the strength of collaboration between the respective countries. The size of the nodes is directly proportional to the total number of publications originating from the corresponding country. The color-coding of the nodes represents different clusters of international collaboration within the research field.

The analysis reveals that countries are ranked based on the number of published documents, citations received, and total link strength. China leads with 2,835 documents and 43,676 citations, indicating a substantial research presence in this field. The United States follows, with 981 documents and 25,702 citations, demonstrating its growing contribution. India and Australia also emerge as significant contributors. Furthermore, the presence of countries like England, South Korea, and Iran highlights the global nature of this research area. The "total link strength" is likely a composite measure, potentially derived from co-authorship or citation patterns, reflecting the interconnectedness of research activities across these countries.

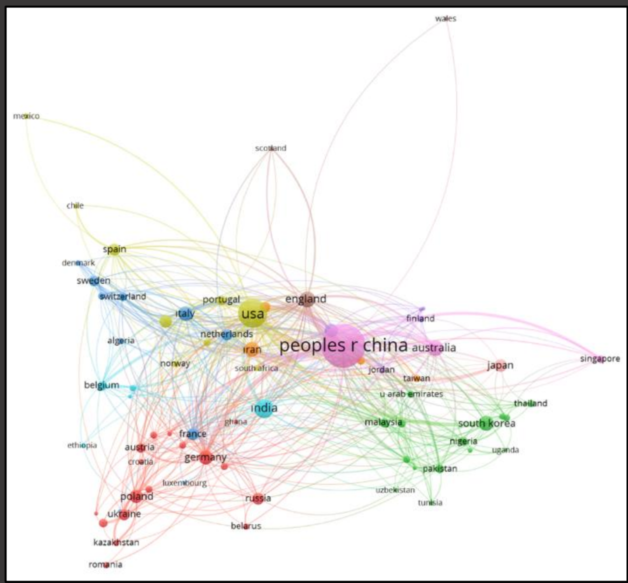

Figure 3. Analysis of countries with the most publications.

The visualization in Figure 3 shows that the largest nodes represent the countries with the most publications in the research area. The prominent size of nodes for countries like "People's Republic of China," "USA," and "England" suggests that these nations are major research centers in the fields of "pavement," "composite," and "geosynthetics," producing a significant volume of scholarly publications.

The visualization's colored nodes suggest that countries with nodes of the same hue demonstrate a greater degree of collaborative activities among themselves. For instance, countries grouped within a particular color cluster may have participated in more joint research projects or co-authored publications. These clusters could signify regional collaborations or international partnerships formed around specific research foci.

The width of the connections between the nodes reflects the intensity of collaboration between the countries. Thicker lines signify a greater number of co-authored publications, indicating a stronger scientific partnership between the two nations. For example, the prominent connection between "China" and "Australia" suggests a significant research collaboration between these two countries. Similarly, the robust link between the "United States" and "England" demonstrates that they are also major collaborative partners in the field.

The central countries with extensive connections to numerous other nations are at the core of international research collaboration within this field. Prominent examples include "People's Republic of China," "USA," and "England," which occupy this pivotal position due to their substantial publication output and extensive collaborative networks. In contrast, countries situated on the periphery of the visualization with fewer connections may play a more peripheral role in international collaboration. However, this does not necessarily indicate a lack of contribution; they may be focused on more specialized or regional research partnerships.

The analysis of collaboration clusters suggests that geographical proximity and shared research priorities may shape collaboration patterns. Countries within the same geographic region or those focusing on similar research domains tend to exhibit a stronger tendency for collaborative activities.

The visualization effectively highlights the leading countries in terms of research productivity and international collaboration within the fields of "pavement," "composite," and "geosynthetics." China, the United States, and England emerge as the most prolific publishers and prominent collaborative partners. The clustering of countries by color suggests distinct patterns of international research cooperation, while the thickness of the linkages indicates the strength of these collaborative relationships. This analysis offers valuable insights into the global research landscape in these domains and can inform potential future avenues for collaborative engagement.

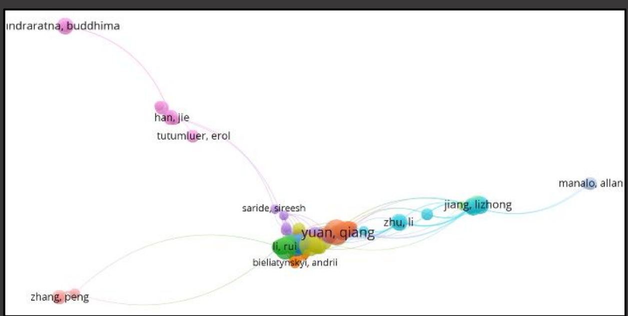

Figure 4. Analysis of Author Citation Networks and Influence

3.4. Analysis of author citation networks and influence

The visualization in Figure 4 is the result of an "author citation network" analysis conducted using VOSviewer on bibliometric data retrieved from the Web of Science database using the keywords. This network map illustrates the most prominent and influential authors in these research areas, as well as the intricate citation relationships between them. Each author is represented by a node, and the lines connecting the nodes indicate the frequency of citations between the authors or the number of times they have been cited together in shared publications. The size of the nodes is directly proportional to the total number of citations received by the respective author, highlighting their impact and significance within the research community. The color-coding of the nodes represents different clusters of authors who have a strong collaborative or citation-based relationship, suggesting the formation of research communities or schools of thought within the field. Figure 4 presents the most cited researchers in the field, considering 181 researchers with at least eight publications and five citations. The most highly cited researcher is Wu, Shaopeng, who has made a significant impact with his contributions. Following Shaopeng (1383), in descending order of citation count, are Indraratna, Buddhima (995); Yuan, Qiang (899); Bhasin, Amit (725); Oeser, Markus (689); Han, Jie (681); Li, Wengui (671); and Tan, Yiqiu (668). These authors have also emerged as influential figures within the research community, demonstrating their substantial influence and recognition among their peers.

The visualization in Figure 4 prominently displays the authors who have garnered the most citations within the research area. For instance, the sizeable node representing "Yuan, Qiang" suggests that this scholar has made substantial and impactful contributions to the fields of "pavement," "composite," and "geosynthetics," with their work frequently referenced by other researchers. Similarly, the larger nodes correspond to other highly influential authors in the field.

The nodes in different colors group authors with similar citation patterns. Authors in the same color cluster have closely related work, likely focusing on similar topics or influencing each other's research. These clusters represent different research groups or schools of thought within the field.

The lines connecting the nodes represent the citation relationships between authors. The thickness of the lines can indicate the number of times one author has cited another or the frequency with which two authors' works are co-cited. Thicker lines suggest a stronger scientific influence or conceptual relationship between the respective authors. For example, the prominent link between "Yuan, Qiang" and "Zhu, Li" suggests that their works have a significant interaction within the field.

Researchers situated at the center of the author citation network, with numerous connections to other scholars, occupy a pivotal role in the field's knowledge dissemination and scientific collaboration. Highly cited authors with extensive citation linkages serve as crucial reference points within the research area. In contrast, researchers positioned on the periphery of the visualization, with fewer connections, may concentrate on more specialized topics or be relatively newer contributors to the field.

Analysing author citation networks is a vital approach for assessing an author's scientific influence and prominence within a research domain. Scholars with extensive citation counts and robust citation connections have often made seminal contributions to the field's advancement and exerted a profound impact on their peers.

The visualization provides a comprehensive depiction of the most influential and highly cited authors within the research domains of "pavement," "composite," and "geosynthetics," while also illustrating the intricate citation relationships among them. Prominent scholars, such as" Yuan Qiang," occupy central positions in the network, indicating their significance and impact within the field. The distinct color-coded clusters suggest the formation of research communities or schools of thought, showcasing scholars with closely related citation patterns and collaborative ties. Furthermore, the thickness of the citation linkages underscores the strength of scientific interactions between authors, highlighting the foundational references and impactful researchers in these research areas. This analysis serves as a valuable resource for understanding the intellectual structure and influential contributors within the field.

3.5. Most cited publications

This visualization in Figure 5 presents the results of a "most cited publications" analysis conducted using VOSviewer. The analysis was performed on bibliometric data retrieved from the Web of Science database, using the keywords "pavement," "composite," and "geosynthetics." The network map illustrates the most frequently cited scientific publications within these research domains and the citation relationships between them. Each publication is represented by a node, labeled with the first author's last name and the publication year. The connections between the nodes indicate the frequency with which one publication has cited another or the degree to which both publications are cited together by the same sources. The size of the nodes is proportional to the total number of citations received by the respective publication, highlighting the impact and significance of the most influential works. The color-coding of the nodes represents different clusters of publications based on their citation linkages, suggesting the presence of related scholarly groups or areas of focus within the field.

Figure 5 presents the most cited publications within the research domains of "pavement," "composite," and "geosynthetics." Out of a total of 6,050 publications analyzed, 2,601 publications with at least ten citations were found, and 896 of these publications were taken into consideration for this analysis.

Examining the Figure 5, it can be seen that the most cited publication is that of Adachi. This highly influential work is followed, in descending order of citation count, by the publications of Yang, Kreider, Yang, Kolias, Wu, Qian, de Brito, Leite, Indraratna, Yang, Gui, and McDowell. Details about these publications are given in Table 1. These publications have garnered significant attention and impact within the research community, reflecting their importance and contribution to the field.

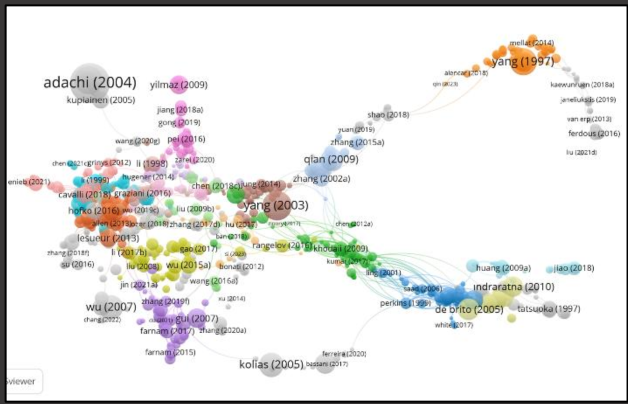

Figure 5. Most cited publications

The most prominent nodes in the visualization in Figure 5 correspond to the publications that have accumulated the highest citation counts within the research domain. For instance, the sizeable nodes for "Yang" and "Adachi" suggest that these works are foundational and impactful contributions in the fields of "pavement," "composite," and "geosynthetics," with their findings frequently referenced by other scholars. These heavily cited publications may represent seminal works or fundamental theoretical frameworks that have significantly advanced the understanding in these research areas.

The colored nodes show groups of publications that are closely related based on how they cite each other. Publications in the same color group are more closely connected, likely focusing on similar topics, using the same research methods, or building on each other's work. These groups can represent different research areas or subfields within the broader field.

The lines connecting the nodes in the visualization represent the citation relationships between the publications depicted. The thickness of these lines can signify the frequency with which one publication has cited another or the degree to which two publications' works have been co-cited. Thicker lines, therefore, suggest a stronger scientific influence or conceptual relationship between the respective publications. For instance, a prominent link between two specific publications indicates that they have significantly influenced each other or made substantial contributions to the same scholarly discourse within the field.

Publications situated at the center of the visualization, with connections to numerous other publications, lie at the heart of knowledge exchange and scientific collaboration within the field. Highly cited publications with extensive citation linkages serve as foundational reference points in the research area. Conversely, publications positioned on the periphery of the visualization, with fewer connections, may concentrate on more specialized topics or may represent more recent contributions to the field.

The years on the publications indicate when these works were published. The distribution of the most cited publications across different years can help understand the temporal impact and longevity of foundational works in the field. Publications from earlier years that still receive a high number of citations may represent classic studies that form the basis of the field.

This visualization provides a comprehensive overview of the most influential and frequently cited publications within the research areas of "pavement," "composite," and "geosynthetics." The central publications with larger node sizes represent the foundational and impactful works that have significantly contributed to the field. The distinct color-coded clusters indicate the formation of research communities or schools of thought, showcasing scholars with closely related citation patterns and collaborative ties. Furthermore, the thickness of the citation linkages underscores the strength of scientific interactions between authors, highlighting the seminal references and prominent researchers in these research domains. This bibliometric analysis serves as a valuable resource for understanding the intellectual structure, influential contributors, and key trends within the field.

3.6. Distribution of publications over the years

Figure 6 presents a visual representation of the distribution of publications obtained from the Web of Science database using the keywords "pavement, composite, and geosynthetics" across different years. This graphical depiction clearly illustrates the temporal trend of scientific productivity within the research area. The graph depicts a clear and sustained upward trend in the number of publications within the research area. This upward trajectory has notably accelerated, especially in the period following 2018. The distribution of publications by year is also given in Table 2.

Table 1. Most cited publications (top 10)

Author Full Names	Article Title	Cite
Adachi, K; Tainosho, Y	Characterization of heavy metal particles embedded in tire dust	730
Yang, J; Jiang, GL	Experimental study on properties of pervious concrete pavement materials	422
Kreider, M.L., Panko, J.M., McAtee, B.L., Sweet, L., & Finley, B.L.	Physical and chemical characterization of tire-related particles: Comparison of particles generated using different methodologies	381
Yang, YB; Yau, JD; Hsu, LC	Vibration of simple beams due to trains moving at high speeds	364
Kolias, S; Kasselouri-Rigopoulou, V; Karahalios, A	Stabilisation of clayey soils with high calcium fly ash and cement	300
Wu, S., Xue, Y., Ye, Q., & Chen, Y.	Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures	299
Qian, S.; Zhou, J.; de Rooij, M. R.; Schlangen, E.; Ye, G.; van Breugel, K.	Self-healing behavior of strain hardening cementitious composites incorporating local waste materials	256
de Brito, J; Pereira, AS; Correia, JR	Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates	233
Leite, F.D., Motta, R.D., Vasconcelos, K.L., & Bernucci, L.L.	Laboratory evaluation of recycled construction and demolition waste for pavements	216
Indraratna, B., Nimbalkar, S.S., Christie, D., Rujikiatkamjorn, C., & Vinod, J.S.	Field Assessment of the Performance of a Ballasted Rail Track with and without Geosynthetics	212

Table 2. Distribution of publications by year between 2001 and 2025

Publication Years	Record Count	% of 6.050	Publication Years	Record Count	% of 6.050
2001	21	0,35	2014	183	3,02
2002	41	0,68	2015	188	3,11
2003	35	0,58	2016	215	3,55
2004	35	0,58	2017	238	3,93
2005	43	0,71	2018	313	5,17
2006	41	0,68	2019	399	6,6
2007	52	0,86	2020	500	8,26
2008	57	0,94	2021	569	9,4
2009	81	1,34	2022	662	10,94
2010	97	1,6	2023	711	11,75
2011	96	1,59	2024	873	14,43
2012	128	2,12	2025	216	3,57
2013	130	2,15			

Table 3. Top 10 Most Cited Publications

Title	Authors	Source Title	Publication Year	Total Citations	Average Citations per Year
Characterization of heavy metal particles embedded in tire dust	Adachi, K.; Tainosho, Y.	ENVIRONMENT INTERNATIONAL	2004	730	33,18
Experimental study on properties of pervious concrete pavement materials	Yang, J.; Jiang, GL	CEMENT AND CONCRETE RESEARCH	2003	423	18,39
Physical and chemical characterization of tire-related particles: Comparison of particles generated using different methodologies	Kreider, Marisa L.; Panko, Julie M.; McAtee, Britt L.; Sweet, Leonard I.; Finley, Brent L.	SCIENCE OF THE TOTAL ENVIRONMENT	2010	382	23,88
Challenges Toward Wireless Communications for High-Speed Railway	Ai, Bo; Cheng, Xiang; Kuemer, Thomas; Zhong-Dui; Guan, Ke; He, Rui-Si; Xiong, Lei; Matolak, David W.; Michelson, David G.; Briso-Rodrigues, Cesar	IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS	2014	378	31,5
Durability performances of concrete with nano-silica	Du, Hongjian; Du, Sujuan; Liu, Xuemei	CONSTRUCTION AND BUILDING MATERIALS	2014	332	27,67
Automatic Crack Detection on Two-Dimensional Pavement Images: An Algorithm Based on Minimal Path Selection	Amhaz, Rabih; Chambon, Sylvie; Idier, Jerome; Baltaart, Vincent	IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS	2016	328	32,8
Fundamentals of soil stabilization	Firoozi, Ali Akbar; Olgun, C.; Funezy, Firooz; Ali Asghar; Baghini, Mojtaba Shojaei	INTERNATIONAL JOURNAL OF GEO-ENGINEERING	2017	307	34,11
Stabilisation of clayey soils with high calcium fly ash and cement	Kolias, S.; Kasselouri-Rigopoulou, V.; Karahalios, A.	CEMENT & CONCRETE COMPOSITES	2005	300	14,29
Utilization of steel slag as aggregate for stone mastic asphalt (SMA) mixtures	Wu, Shaopeng; Xue, Yongjie; Ye, Qunshan; Chen, Yongchun	BUILDING AND ENVIRONMENT	2007	299	15,74
Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement	Huang, BS; Li, GQ; Vukosavljevic, D; Shu, X; Egan, BK	BITUMINOUS PAVING MIXTURES	2005	286	13,62

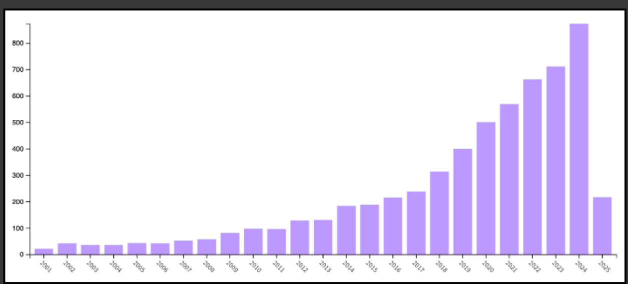

Figure 6 Distribution of publications over the years

3.7. Distribution of Citations and Publications by Year

The distribution of citations across publications from different years offers valuable insights into the enduring impact and significance of research within the specified field. The distribution of the most cited publications across different years can help understand the temporal impact and longevity of foundational works in the field. Figure 7 provides a visual representation of the annual trends in scientific publications and the total citations received by these publications related to "pavement, composite, and geosynthetics" from 2000 to 2025. Accompanying this, Table 3 presents details on the top 10 most highly cited publications from the same dataset, including information on their titles, authors, source titles, publication years, total citations, and average citations per year. The graph in Figure 7 clearly demonstrates a significant and sustained increase in both the number of publications and the citations they have received over time, with the growth rate of citations outpacing that of publications. Complementing this overall trend, the top 10 most cited publications in Table 3 offer more specific insights into the foundational and impactful works that have shaped the field.

The graphical depiction in Figure 7 clearly illustrates a distinct upward trend in both the volume of publications and the associated citation count over time. Notably, the rate of increase in citations appears to outpace the growth in the number of publications. The publication trend exhibits a gradual ascent, transitioning from relatively low levels in the early 2000s to a pronounced acceleration, particularly after 2018. The publication count reached its peak in 2024, with approximately 873 records, signaling a substantial surge in research interest and scientific productivity within this field in recent years. The lower publication count for 2025 can be attributed to the fact that the year is not yet complete, and the full picture is yet to emerge. The citation count has also exhibited a concurrent upward trajectory alongside the growth in publications, but with a markedly accelerated pace, particularly after 2015. By 2024, the total citation count had reached approximately 20,000. This suggests that more recent scholarly contributions have garnered heightened attention and are being referenced more frequently compared to earlier works. It is also plausible that certain foundational studies published during the initial period continue to maintain a strong citation impact over time. The graphical trend indicates that although the number of publications has recently declined, these fewer papers are garnering a disproportionately greater number of citations relative to the more voluminous output in earlier years. This observation may suggest several possibilities: a deepening of research focus within the field, the emergence of more impactful and influential studies, or a greater concentration on specific research topics gaining prominence.

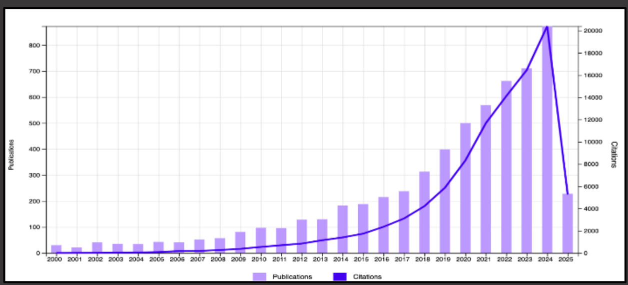

Figure 7. Distribution of Citations and Publications by Year (2000-2025)

The top publications in Table 3 have received a substantial number of citations, reflecting their significant influence and impact within the field compared to other works. For example, the 2004 publication by Adachi et al., titled "Characterization of heavy metal particles embedded in tire dust," has garnered 730 citations. Similarly, the 2003 study by Yang and Jiang, "Experimental study on properties of pervious concrete pavement materials," has received 423 citations. These highly cited publications have likely made pioneering contributions by introducing important research topics and methodologies that have shaped the direction of scholarship in this domain. The data in the Table 3 indicates that publications from earlier years typically have accumulated a higher total number of citations. This can be attributed to the longer duration during which they have been available for other researchers to reference and build upon. Nevertheless, the Table 3 also reveals that some more recent publications from 2010 and onwards have garnered substantial citation counts, underscoring the notable influence and impact of contemporary scholarship within this field. For instance, the 2010 study by Kreider et al. has been cited 382 times, demonstrating the significant contributions of more recently published works. The "Average Citations per Year" column offers a valuable metric for assessing the impact of publications of varying ages. This metric reveals the average number of citations a work has received annually since its publication, enabling a more equitable comparison across studies. For instance, the 2016 publication titled "Automatic Crack Detection on Two-Dimensional Pavement Images: An Algorithm Based on Minimal Path Selection" has accumulated a high average citation rate per year, despite its relatively recent publication. This suggests that the study has significantly influenced and informed ongoing research, despite its short time in circulation. The publication titles listed in the Table 3 demonstrate the extensive range of research topics explored within this field. The inclusion of highly cited works that investigate the characterization of heavy metal particles in tire dust, the properties of pervious concrete pavements, the analysis of tire-related particles, wireless communication systems for high-speed railways, the durability of nano-silica concrete, pavement crack detection methods, soil stabilization techniques, the stabilization of clayey soils, the utilization of steel slag, and the incorporation of reclaimed asphalt pavement collectively reflects the broad scope of research interests and priorities within this domain.

4. Discussion and Conclusions

This bibliometric investigation, drawing upon data from the Web of Science database on publications pertaining to "pavement, composite, and geosynthetics," offers a comprehensive portrayal of the intellectual landscape, key contributors, and emerging trends within this critical domain of transportation infrastructure engineering. The escalating global demand for resilient and sustainable transportation networks has prompted substantial research efforts aimed at enhancing pavement performance through innovative materials and techniques, as underscored in the introduction [1, 105]. The significant attention afforded to composite and geosynthetic materials for reinforcing pavement structures, as noted by [3] and [4], is evidently reflected in the bibliometric data.

The keyword analysis illuminates the central themes and interconnected concepts within this research domain. The clustering of terms such as "asphalt mixture," "mechanical properties," and "rheological properties" highlights the fundamental emphasis on material characterization and performance optimization. The prominence of "pavement," "composite," and "geosynthetics" underscores their significance as primary areas of inquiry. Furthermore, the emergence of keywords like "sustainability" and "recycling" suggests a growing awareness and integration of environmental considerations within pavement engineering research.

The co-authorship analysis illuminates the collaborative structures among researchers in this domain. By identifying central authors and distinct collaboration clusters, it suggests the presence of active research groups and international partnerships that are driving innovation forward. Key figures like Yuan Qiang, who exhibits the highest number of co-authorships, as well as other prolific co-authors, have emerged as central nodes within the collaborative network. Researchers occupying central positions, such as Yuan, Qiang, Pei, Jianzhong, Wu, Shaopeng, and Yang, Jun, have established themselves as hubs of collaboration, indicating their prominence and influence in shaping the research landscape. Understanding these collaborative patterns can facilitate the initiation of future research endeavors and foster knowledge exchange within the community. The co-authorship analysis provides valuable insights into the social and intellectual connections among scholars.

The analysis of highly cited authors highlights the pioneering scholars whose groundbreaking work has significantly shaped the trajectory of research in this field. The most highly cited author, Wu Shaopeng, has made remarkable contributions that have had a substantial impact. Other influential authors include Indraratna, Buddhima; Yuan, Qiang; Bhasin, Amit; Oeser, Markus; Han, Jie; Li, Wengui; and Tan, Yiqiu. Acknowledging the contributions of these leading scholars is crucial for comprehending the historical evolution and foundational theoretical frameworks within the research domain. By identifying these influential figures, we can better understand the key ideas, methodologies, and conceptual breakthroughs that have driven the development of this research area over time.

An examination of the most frequently cited publications further reinforces the identification of foundational work and influential studies within this field. These highly impactful publications often represent methodological advancements, critical research findings, or comprehensive reviews that have significantly shaped the trajectory of subsequent investigations. As detailed in Table 1, the most frequently cited publication was by Adachi, followed by works from Yang, Kreider, Kolias, Wu, and others. Scrutinizing the content and impact of these influential studies can provide valuable insights into the core knowledge base underlying the field. By delving into the specific contributions and key takeaways of the most heavily cited publications, we can better understand the seminal ideas, critical breakthroughs, and established best practices that have defined the progression of this research domain over time. This deeper exploration of the literature can shed light on the conceptual foundations, empirical evidence, and theoretical frameworks that have been instrumental in advancing the field of pavement engineering, particularly with respect to the utilization of composite and geosynthetic materials.

The analysis of publication trends over time reveals a substantial increase in research activity, particularly from 2018 onwards. This upward trajectory indicates a growing global emphasis on addressing the challenges faced by pavement infrastructure through the utilization of composite and geosynthetic materials. The surge in recent years can be attributed to advancements in material science, the evolution of construction techniques, and an elevated focus on developing sustainable and long-lasting infrastructure solutions.

This bibliometric study provides valuable insights into the dynamic and expanding field of pavement engineering, with a specific focus on composite and geosynthetic materials. The findings highlight the central research themes, influential scholars, significant publications, and the accelerating trend of scholarly output. This understanding can guide future research directions, foster collaborations, and ultimately contribute to the development of more resilient, sustainable, and economically viable transportation infrastructures, aligning with the overarching objectives of economic advancement and societal well-being. The continued exploration and integration of advanced materials and techniques in pavement engineering remain crucial for addressing the evolving demands of transportation networks worldwide.

Declaration of Interest Statement

The author declare that s/he have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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