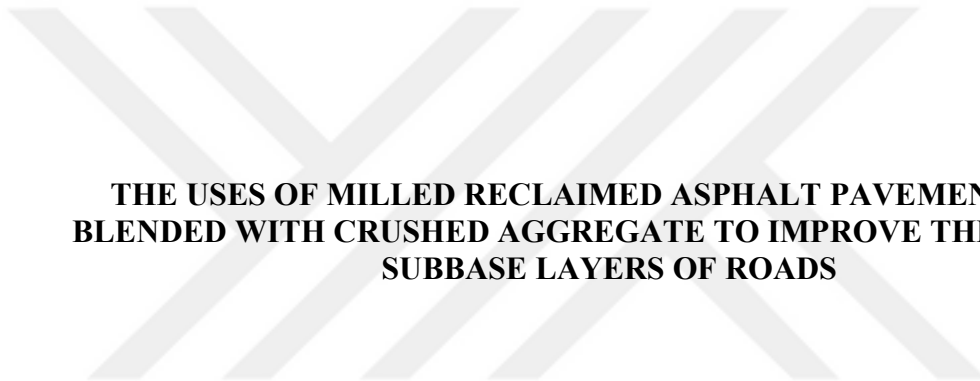


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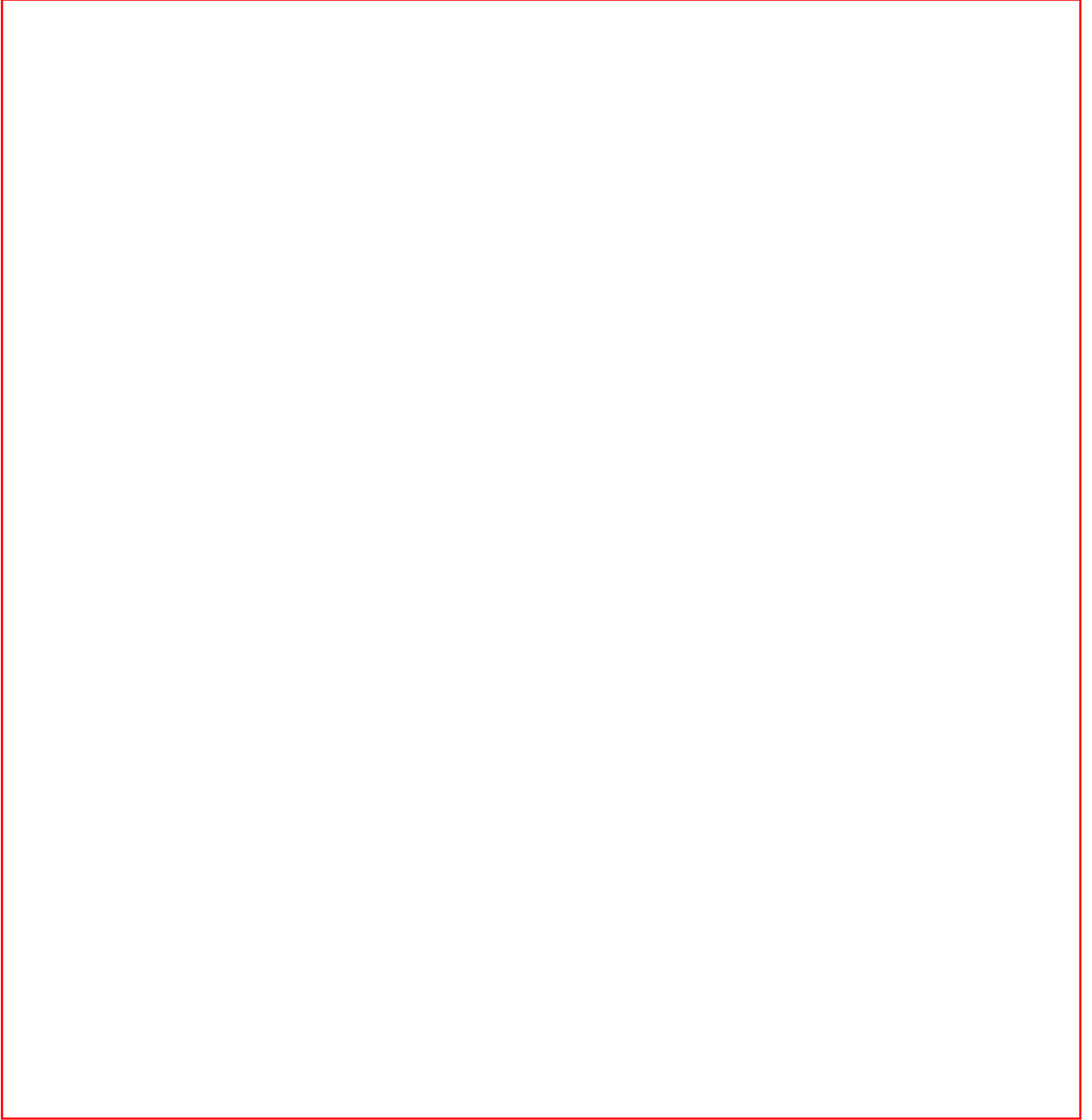


**THE USES OF MILLED RECLAIMED ASPHALT PAVEMENT (RAP)
BLENDED WITH CRUSHED AGGREGATE TO IMPROVE THE BASE OR
SUBBASE LAYERS OF ROADS**

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DEPARTMENT OF CIVIL ENGINEERING

**ŞANLIURFA
2022**



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ÖZET

Yüksek Lisans Tezi

YOLLARIN TEMEL VEYA ALT TEMEL KATMANLARINI İYİLEŞTİRMEK İÇİN EZİLMİŞ AGREGA İLE KARIŞTIRILMIŞ FREZELENMİŞ YENİLENMİŞ ASFALT KAPLAMA (RAP) KULLANIMI

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Tipik olarak, kaldırım rekonstrüksiyonu ve rehabilitasyonu sırasında daha önemli miktarlarda geri kazanılmış asfalt kaplama agregası üretilir ve RAP geri dönüşümü bu yaklaşımda kullanılan standart bir teknolojidir. Yollar sürekli bakım gerektirir ve yöntemlerden biri yol yüzeylerini taramaktır. Bununla birlikte, laboratuvar ve saha performansı verilerinin çok değerli olması nedeniyle, yol tabanlarında ve alt tabanlarda RAP benimsemesi sınırlandırıldı. Genel olarak, Irak'ın Erbil kentinde kaldırım malzemelerinin geri dönüşümü uygulanmıyor. Yolun tabanındaki ve alt taban katmanındaki malzemeleri yeniden kullanmak için, ezilmiş agrega ile karıştırılmalı ve karıştırılmalıdır. Bu amaçla karma numuneler toplandı ve test edildi. Sonuçlara göre, ezilmiş agrega ve Çimento'nun dahil edilmesi optimum nem içeriğini, maksimum kuru yoğunluğu ve RAP'in gücünü artırır. Daha uzun süre kütleme daha önemli sonuçlara neden olacaktır. Sürekli kafa geçirgenliği testlerinin sonuçlarına göre RAP yüzdesinin yükseltilmesi geçirgenlik katsayısını azalttı. RAP karışımlarının geçirgenliğinin azalması, RAP karışımlarının ezilmiş agregaya göre daha düşük boşluk oranları ile açıklanmıştır.

ANAHTAR KELİMELE: Kaliforniya rulman oranı, Çimento, Ezilmiş agregalar, Geçirgenlik, Geri kazanılmış asfalt kaplama.

ABSTRACT

MSc Thesis

THE USES OF MILLED RECLAIMED ASPHALT PAVEMENT (RAP) BLENDED WITH CRUSHED AGGREGATE TO IMPROVE THE BASE OR SUBBASE LAYERS OF ROADS

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Typically, more significant amounts of reclaimed asphalt pavement aggregate are produced during pavement reconstruction and rehabilitation, and RAP recycling is a standard technology Utilized in this approach. Roads require continual maintenance, and one of the methods is to screen The road surfaces. However, due to a dearth of laboratory and field performance data, RAP adoption in road bases and subbases has been limited. In general, recycling pavement materials is not practiced in Erbil, Iraq. To reuse the materials in the Road's base and subbase layer, they must be blended and mixed with crushed aggregate. A collection of mixed samples was collected and tested for this purpose. According to the results, the inclusion of crushed aggregate and Cement increases the optimum moisture content, maximum dry density, and strength of RAP. Curing for longer lengths of time will result in more substantial results. According to the results of constant head permeability tests, raising the RAP percentage decreased the coefficient of permeability. The reduced permeability of RAP mixtures was explained by the lower void ratios of RAP mixtures compared to crushed aggregate.

KEY WORDS: California bearing ratio, Cement, Crushed aggregates, Permeability, Reclaimed asphalt pavement

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SYMBOLS and ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CO ₂	Carbon Dioxide
°C	Centigrade
COTS	Commercial Off-The-Shelf
CA	Crushed Aggregates
°F	Degrees Fahrenheit
FHWA	Federal Highway Administration
IRI	International roughness index
MDD	Maximum Dry Density
NRL	Natural Rubber Latex
OMC	Optimum Moisture Content
PCI	Pavement Condition Index
PMS	Pavement Management System
PQI	Pavement Quality Index
PSI	Present Serviceability Index
PSD	Proprietary Systems Developed
RAP	Reclaimed Asphalt Pavement

1. INTRODUCTION

1.1. Background of the Study

Several bituminous pavement rehabilitation methods have been introduced over the past two or more centuries with the goal of protecting pavement geometrics (Yu-Shan, and Shakiba, 2021), preserving binder and aggregate (Mousa et al., 2021), reducing construction costs (Seferoglu et al., 2018), conserving energy and reducing user delay (Thakur, 2011). Subsequently, three bituminous pavement rehabilitation methods exist and cater for such purposes, and these are reconstruction, recycling, and overlaying (Aravind and Das, 2006). Nevertheless, costs attached to reconstruction and overlaying methods are presumed to be excessive (Saladhi, 2017). Some studies consider reconstruction and overlaying methods as unsustainable (Sheikh et al., 2021; Wu et al., 2012). As a result, recycling is highly favorable, and its importance is linked to cost reduction and sustainability (Sheikh et al., 2021). Other studies also show that recycling pavements are essential for improving road safety and reducing damage to motor vehicles (Thakur, 2011; Yu-Shan, and Shakiba, 2021).

One of the critical areas that several studies have been analyzing to enhance pavement effectiveness is Reclaimed Asphalt Pavement (Mousa et al., 2021; Seferoglu et al., 2018; Thakur, 2011; Yu-Shan and Shakiba, 2021). As such, studies reckon that additional benefits can be obtained when Reclaimed Asphalt Pavement is recycled into forming what is known as Recycled Asphalt Pavement (RAP) (see Ramasamy, 2010; Saladhi, 2017; Sheikh et al., 2021; Wu et al., 2012). This is evident through RAP's increased usage in developing countries like the Netherlands, Denmark, and the United States of America, where 12 million tons, 53 tons, and 33 million tons of RAP are recycled annually (Aravind and Das, 2006).

It is crucial at this stage to establish and set a solid foundation by acknowledging that recycling processes are used in classifying RAP recycling methods. This is evident in (Aravind and Das', 2006) study highlighting that RAP recycling methods are classified according to (1) hot process and (2) cold process. Additionally, attention needs to be given to the places where the RAP is modified as it can be modified away from the plant (central plant recycling) and at the plant (in-plant recycling). Either a hot process or cold process is applied in both central plant recycling and in-plant recycling situations (Aravind and Das, 2006).

Nevertheless, there is significant importance and huge benefits obtainable by analyzing the performance of RAP. This is congruent to a growing number of studies advocating that the performance of RAP be analyzed in terms of its permeability, density, and bearing (Mousa et al., 2021; Seferoglu et al., 2018; Thakur, 2011; Yu-Shan and Shakiba, 2021). Much of these benefits are obtainable when crushed aggregates are introduced (Seferoglu et al., 2018), and cement is used to treat the RAP (Yu-Shan and Shakiba, 2021). It is in this regard that this study intends to examine RAP when combined with crashed aggregates are introduced and treated the RAP is treated with cement. This will be done in the context of Erbil-Iraq, which lacks supporting studies concerning the use and performance of RAP.

1.2. Research Problem

Analyzing and suggesting that RAP is vital as compared to other methods related to the reconstruction and overlaying methods (Seferoglu et al., 2018). However, such considerations are inadequate when the focus is not given to the performance of the RAP. Additionally, (Seferoglu et al., 2018) assert that much remains to be established regarding the performance of RAP when factors like permeability, density, and bearing are considered. These crucial considerations are not widely evident in related studies, especially when analyzed in the context of Iraq. Furthermore, not much is known about the performance of RAP when stabilized with various cement and the optimal material

combinations required to enhance the adequate performance of RAP. These empirical voids call for detailed experimental examinations that this study strives to fill. Consequently, the study's novelty and originality are crafted in its capacity to fill these empirical voids in the context of Erbil-Iraq.

1.3. Research Questions

Given the problems mentioned above, the study, therefore, strives to answer the following questions;

- Is there a possibility of using Reclaimed Asphalt Pavement together with crash aggregate to improve the performance of the base course layer? If so, then how can high-quality crushed aggregate materials and/or adding chemical stabilizing agents (cement) be utilized to strengthen RAP as a component of road base courses?
- What are the best optimal RAP-crash aggregate and chemical stabilizing agent combinations capable of effectively enhancing the quality and performance of the base course layer with regards to?
 1. The bearing capacity.
 2. Permeability capability.
- Is the selected optimal RAP-crash aggregate combination suitable for use in Iraq?

1.4. Scope of the Study

The study is confined to the examination of reclaimed asphalt pavement's performance. Three materials in the form of reclaimed asphalt pavement (RAP), crashed aggregates (CA), and cement was used for fulfilling the study's objectives. Such efforts were made possible by the application of the proctor test comprising of the Optimum

Moisture Content (OMC), and Maximum Dry Density (MDD) approaches California Bearing Ratio (CBR), and the Constant Head Permeability test. In addition, the RAP blends were treated with Pozzolanic Cement (Ts En 197-1:2012 Cem Iv/B (P-V) 32,5 N) in the proportions of 1%, 1.5%, 2.5%, and 4% and subjected to a series of tests to analyze the effects on the RAP. All these tests and examinations were conducted in line with ASTM guidelines and standards for conducting the MDD (ASTM D1557-12), OMC (ASTM D2216-06), CBR (ASTM D1883-07), and permeability test (ASTM D2434-68) tests. Additionally, both tests were applied in an original setting of Erbil-Iraq that is widely neglected by related empirical examinations.

1.5. Significance of the Study

The study plays a crucial role in enhancing understanding regarding the role and significance of pavement rehabilitation methods. Besides, the related benefits obtainable from pavement recycling can be improved when RAP is given adequate attention. Hence, the study contributes towards the development of cost-effective, sustainable, and high-performing pavement recycling methods. Moreover, this study can set a stage on which other future studies can remodel ideas and experimental methods to produce solid and reliable suggestions capable of producing optimal RAP and crash aggregates combination that can enhance the performance of RAP.

2. LITERATURE REVIEW

2.1. Introduction

This chapter provides theoretical ideas guiding the role and problems of reclaimed asphalt pavements (RAP), how related issues can be determined using methods like the Pavement Condition Index (PCI), and associated solutions encompassing pavement preservation and maintenance and rehabilitation methods. Such results in establishing shortfalls with RAP materials leading to propositions advocating for the application of cement stabilization methods. These ideas are further examined and evaluated using related empirical studies.

2.2. The Role of Reclaimed Asphalt in Existing Pavements

Recycled materials have been increasingly used in the base layers of asphalt pavements. The application of hot-in and cold-in place recycling makes it feasible for them to be used in urban and rural road pavements (Tarsi et al., 2020). Reclaimed asphalt is produced by combining asphalt with limited amounts of additive materials. Consequently, Reclaimed Asphalt Pavements (RAP) is claimed to offer substantial benefits compared to other pavement materials because of its potency to eliminate the need to use asphalt and aggregates in existing pavements (Hasan et al., 2020).

RAP possesses unique physical properties that give its individual pavement enhancement roles. RAP's physical properties capable of improving road pavements' performance were listed as moisture content and water immersion (Oliveira and Correia, 2008). Other physical properties such as sand equivalence and gradation are documented in previous examinations (Janani et al., 2021). Other vital features can significantly enhance pavement performance, including toughness, specific gravity, and Atterberg limits (Chhabra et al., 2021). These properties are linked to the following benefits;

- **Economic benefits:** RAP is cost-effective compared to other pavements materials like virgin aggregates. Studies highlight that RAP eliminates the need to replace the affected binder's virgin aggregate part, thus, reducing material costs (Bressi et al., 2021; Janani et al., 2021). Furthermore (Oliveira and Correia, 2008) contend that RAP can be transported at a relatively lower cost. It can be supported by study findings made by (Milad et al., 2020), showing that asphalt mixtures containing 30-50% RAP tend to reduce maintenance costs by US \$58,000/km. Previous studies widely prove these economic benefits. Milad and others also contend that there is a possibility of lowering rehabilitation and maintenance costs by 30% by applying RAP as a base material in pavements. It can be reinforced by (Freitas et al., 2018) observations showing that using RAP reduces the need to use expensive asphalt binders.
- **Environmental benefits:** It is highly evident in academic research that RAP offers various and significant environmental benefits. One key benefit relates to its ability to reduce the demand and use of non-renewable resources (Chhabra et al., 2021). Hasan et al. (2020) outlined that RAP is recyclable and thus, eliminates the need to dispose of it in landfills (Cafiso et al., 2019). Saha and Mandal (2017) mentioned that there are reductions in emissions and fuel consumption benefits linked to the use of RAP. (Shi et al., 2018) contend that combining asphalt mixtures with 15% RAP reduces energy consumption and the impact of fossil fuels on climate change by 13-14%. This places RAP as an essential cost-effective material and can contribute to enhancing sustainable environmental management practices.
- **Engineering benefits:** RAP offers substantial engineering benefits compared to other materials such as virgin aggregates. It was documented that RAP enhances the strength of pavements (Milad et al., 2020). Previous studies conducted in places like the USA comparing the performance of virgin aggregates and RAP mixtures showed that mixes containing RAP enhanced the performance of pavements by 30% compared to virgin aggregates (Oliveira and Correia, 2008). The engineering benefits of RAP are also

connected to the types of roads and areas they are used. For instance (Milad et al., 2020), further contend that RAP is suitable for use in freezing and low-temperature regions, while others assert that RAP is ideal for use in non-freezing and high traffic areas (Oliveira and Correia, 2008).

Several studies addressing the effects of RAP tend to relate it to significant and numerous areas, asphalt activities, and aspects. However, the established findings are subject to scrutiny and demand further investigations because the use of RAP in pavements is still in the infancy stages. Additionally, some studies consider RAP as having a negative academic reputation reflected in pavement studies (Freitas et al., 2018; Saha and Mandal, 2017). However, this does not discount the notable benefits of applying RAP materials in asphalt pavement. It can be supported by (Gao et al., 2018), study results showing that incorporating RAP materials in HMA helps to reduce fatigue life.

Furthermore, in a study by (Tebaldi et al., 2018), it is demonstrated that RAP lowers HMA-RAP cracking resistance. These two studies' findings imply that RAP enhances the stiffness of asphalt pavements. According to (Hasan et al., 2020), RAP contains well-graded, high-quality aggregates coated with asphalt cement. In addition, the high moisture content is significantly linked to considerable improvements in pavement performance.

Shi et al. (2018), conducted a study to analyze the permeability of asphalt road pavements mixed with RAP materials. The findings revealed that there is a significant improvement in pavement permeability following an increase in RAP content. Furthermore, suggestions were made in the same study that resilient modulus can also be enhanced by adding RAP. This was subsequently proven right and led to the conclusion that RAP can serve an essential purpose of improving resilient modulus (Cafiso et al., 2019).

Tarsi et al. (2020), focused on analyzing RAP's effects on shear strength and noted that there were substantial improvements in pavements' shear strength following the addition of RAP aggregates. The same study also observed positive changes in resilient modulus and pavement degeneration. The benefits were further extended to other aspects like reducing moisture resistance and rutting (Bressi et al., 2021).

The benefits of using RAP in road pavements are not limited to those listed above. Studies are still ongoing to explore other additional benefits obtained from using RAP in road pavements. However, it is essential to examine how challenges related to old asphalt pavements are instrumental in analyzing the role and significance of RAP aggregates in asphalt pavements. More so, different pavement distresses are presumed to require various pavement materials different from RAP (Chhabra et al., 2021). Thus, the next section of the study examines problems linked to old asphalt pavements to find ways and desirable crushed aggregates and asphalt mix combinations capable of enhancing the performance of road pavements.

2.3. The Problems with Old Asphalt Pavements

Pavements are designed to serve an essential purpose over a lengthy period. However, their use and durability are subject to various conditions influencing their performance and durability. Studies consider that pavements' performance and durability can be compromised, leading to the development of problems like degradation, potholes in roads, and cracks (Cafiso et al., 2019; Freitas et al., 2018; Janani et al., 2021). In most cases, the conditions of road pavements are considered as affected by the volume of traffic passing through that particular place (Mandal et al., 2020). This is of notable concern, especially at a time when globalization, production, and immigration patterns have gradually increased over the past two decades.

Consequently, the rate at which goods and people are transported from one location to another has increased. In such cases, increased traffic volume and loads will

undermine the road's durability and performance (Chhabra et al., 2021). Related empirical studies show that these problems are widely prevalent in road pavements constructed using RAP (Cafiso et al., 2019; Freitas et al., 2018).

A study by Mousa et al. (2021), contends that weather conditions are another critical factor influencing RAP road pavement conditions and pavements. The impact of weather or climate conditions is currently a contemporary concern, as global climate conditions are believed to have worsened over the past three decades (Yu-Shan and Shakiba, 2021). The Intergovernmental Panel on Climate Change (IPCC), During 1300 scientists from the United States and other nations contributed to the study, which predicts a temperature rise of 2.5 degrees Fahrenheit (°F) to 10 degrees Fahrenheit (°F) over the next century. (NASA, 2021). Such is the wake of concerns about rising global emissions that are projected to grow to above 55 gigatonnes of CO₂ equivalent (GtCO_{2e}) per year by the year 2030 from 40 GtCO_{2e}/year (Climate Action Tracker, 2021). Substantial changes in global temperatures pose significant adverse effects on road pavement conditions and performance (Yu-Shan and Shakiba, 2021).

Meanwhile, studies do not spare asphalt pavements from wearing out problems (Freitas et al., 2018; Janani et al., 2021). This creates significant problems, especially when notable concerns are drawn towards the fact that asphalt pavements are too costly to maintain and ensure that they stay in service (Inzerillo et al., 2018). Moreover, it is not a new phenomenon that asphalt pavements fail in numerous typical ways (Cafiso et al., 2020; Mandal et al., 2020; Oliveira and Correia, 2008). The most common include:

- **Fatigue cracking** occurs when repeated strains are developed on the surface due to road traffic loading (Oliveira and Correia, 2008). Alternatively, this is known as an asphalt pavement surface distress failure (Majidifard et al., 2020). Such strains will eventually cause the asphalt to develop cracks on the road surface. Though traffic loading is considered the principal cause of fatigue cracking (Inzerillo et al., 2018)

other environmental factors can cause trigger strains capable of causing the road surface to develop signs of fatigue and cracks (Ragnoli et al., 2018).



Figure 2.1. Fatigue cracking (Aziz, 2016)

Such problems occur because the subbase or base will be incapable of supporting the surface layer and consequently fail to handle loads that it endures under normal circumstances. For example, a study by (Mandal et al., 2020) highlighted that heavy spring thaw causes the subbase or base, while (Janani et al., 2021) assert that the subbase or base is degraded and weakened by poor drainage in the roadbed, as illustrated by Figure 2.1.

- **Rutting:** This occurs when the path of traffic loads shifts the materials in the subgrade, base, and surface, resulting in the formation of ruts or depressions in the asphalt pavement surface (Liley, 2018). Subsequently, the road surface is engraved by a wheel path (see Figure 2.2). Liley (2018) further stated that rutting is caused by weak asphalt mixtures, insufficient pavement thickness, and lack of compaction.



Figure 2.2. Rutting occurring in a road pavement in Iraq

- **Shoving:** This refers to the formation of ripples on an asphalt pavement surface (Nuushuun, 2021). Nuushuun's (2021) study states that such a problem is caused by forces that are generated by trucks and cars stopping and braking, causing the underlying base to separate from the surface material (see Figure 2.3). In addition, empirical studies documented the causes of road shoving. For instance, (Oliveira and Correia, 2008) highlighted that asphalt road pavements are susceptible to shoving because of (1) poor containment of the pavement edge, (2) poor bonds between pavement layers, and (3) inadequate pavement thickness or strength (Majidifard et al., 2020; Ragnoli et al., 2018).



Figure 2.3. Shoving of an asphalt road pavement (Nuushuun, 2021)

- **Loss of foundation or base support:** Insights available in (Freitas et al., 2018) study reveal that pavement bases are bound to fail because of subgrade failure, traffic overloads, or moisture degradation. Such problems occur mainly because the pavement structures are too light, which is usually prevalent in secondary roads (Janani et al., 2021). Additionally (Cafiso et al., 2019) stated that this occurs when the asphalt pavement structures are not designed to cater to current increased traffic levels. According to (Janani et al., 2021), repairing such road pavements using methods like removal and replacement and thick overlays can prove to be costly. Furthermore, (Cafiso et al., 2019) contend that other maintenance treatment methods such as thin asphalt overlay will temporarily cover the problem.
- **Other forms of asphalt pavements failures:** Some studies consider asphalt pavements as susceptible to problems such as disintegration (e.g., potholes, Raveling, etc.) (Mousa et al., 2021), distortions (patch failures, upheaval, depressions), (Yu-Shan and Shakiba, 2021) and other forms of cracking (longitudinal cracking, edge cracking, block cracking, etc.), (Freitas et al., 2018). The occurrence of these problems imposes adverse effects that may prove to be costly for road authorities to maintain. This requires material conservation approaches. The next section of this study looks at material conservation as a wise choice for dealing with asphalt problems.

2.4. Material Conservation: A Wise Choice

It is strategically wise and economically thoughtful to conserve virgin construction materials, and various methods have been put forward for such purposes. However, recycling with cement is considered sensible (Saidu et al., 2020), and this is in the wake of declining aggregate supplies (Dhar and Hussain, 2019), urbanization (Mallick and El-Korchi, 2017), and modern growth (Bansal et al., 2020). Besides, using aggregates is characterized by other prominent problems like mere marginal quality and significant

expenses (Majumder and Venkatraman, 2021). As a result, the continuous use of such materials in building roads can continue to aggravate the problems.

Ekinci (2019), contends that failure to recycle base materials and old asphalt requires that these materials be stockpiled or disposed of. Such approaches are further connected to other problems like utilizing valuable landfill space and increasing transportation costs. This puts pressure to seek and develop other alternatives that are cost-effective, rational, and sustainable. This is evident in (Hunsucker et al., 2017) study, highlighting that certain landfilling activities involving old asphalt are restricted in specific locales. This is relatively true and applicable in contemporary situations where landfilling old asphalt, mining new materials, and strict environmental laws undermine the effective use of old asphalt.

Chaurasia et al. (2021), assert that a recycling-rebuild approach is another self-sustaining process of using old asphalt materials. Initial “investment” in virgin road materials can be a periodically renewed and one-time cost when methods like cement stabilization are applied. Beckham et al. (2020) reckon that using a thin surface course is instrumental as an autonomous method of conserving old materials and reconstructing old asphalt pavements. Some studies consider adding a new as another cost-effective and self-sustaining way of dealing with the challenges of using old asphalt (Bansal et al., 2020).

Saidu et al. (2020), noted that strong foundations for asphalt pavements could be achieved when the underlying subgrade soil, granular base, and old asphalt surface are stabilized cement. A “black gravel” is formed when the old asphalt materials are pulverized, and this eliminates the need to add new asphalt or remove the old asphalt as formed gravel readily bonds to hydrated cement. However, a new asphalt surface can be created by recycling the removed material. Additional aggregates can be combined with the recycled aggregates when the asphalt pavement does not meet the required and acceptable stabilized base standards (Dhar and Hussain, 2019).

Bansal et al. (2020), suggested that the roadway must be scarified depending on the thickness of the existing pavement and construction equipment available before pulverization. However, it is possible to pulverize the asphalt materials without scarifying them using special equipment to perform what is known as quality full-depth recycling. The pulverization process of the subgrade, base, and secondary road surface is conducted at depths between 150 to 300 mm. but this requires that the particles pass a 6-mm (No. 4) sieve by 55% and distributions smaller than 50 mm (Majumder and Venkatraman, 2021).

Dhar and Hussain (2019), contend that the pulverized asphalt material must be shaped to the desired grade and cross-section. In such cases, efforts to widen the roadway will require additional earthwork, and small amounts of the materials may be added or removed to meet the required elevation standards. Finally, measured cement amounts are spread on the shaped roadway's surface in either slurry or dry form.

2.5. Pavement Condition Evaluation

Using RAP must be in line with the stipulated road Pavement Management System (PMS). As a result, methods have been introduced to accomplish such tasks. For example, the Pavement Condition Index (Staniek, 2018) is usually applied in such circumstances (Leiva-Villacorta et al., 2017). However (Marcelino et al., 2018) assert that guidelines must be adhered to when developing a road pavement PCI, which is objectivity and consistency. The objective of applying the PCI must be considered as it influences both criteria and measures to be used during the process.

Additionally, it is vital to ensure that there is consistency in both measurements, application of standards, and processes. Studies consider the attainment of these two critical aspects as challenging (Piryonesi and El-Diraby, 2020; Singh et al., 2018). This is because of a lack of network management data. It is either that the required data is unavailable or is difficult to collect. In the midst of such challenges, road pavement

management authorities and civil engineers can find it complex to compute the PCI of a particular location.

Ragnoli et al. (2018), assert that network management data is always time-consuming and expensive to obtain. Elhadidy et al. (2021) regard the adverse effects of such a situation as hampering initiatives undertaken by any individuals and authorities involved in PMS. This places a considerable demand and complex task of choosing the right and best pavement condition evaluation approach matching their resources and goals (Pantuso et al., 2019). Other concerns also exist and have been raised in prior studies. For instance (Marcelino et al., 2018) contend that automated and manual collection should be used to deal with a situation involving choosing the best pavement condition evaluation approach. Meanwhile (Staniek, 2018) suggested that it is primarily vital to consider the road pavement distress and the available condition indexes when deciding on the best and most-effective Road Management System (RMS) to reduce costs and minimize the utilized resources. These vital aspects are analyzed as follows:

2.5.1. Distresses

Marcelino et al. (2018), attached the importance of using the PCI to determine the nature and magnitude of road distresses. On the other hand (Staniek, 2018) reiterates that different forms of road distress like potholes, patching, surface deterioration, and cracking are easily determined by applying the PCI. In another instance, the Federal Highway Administration (FHWA, 2016) noted that miscellaneous distresses, surface defects, joint deficiencies, and cracking affecting concrete pavement could be examined with the aid of the road pavement PCI. Hence, key significant benefits are linked to the development and assessment of an asphalt road pavement PCI. Table 2.1 provides details of distresses in asphalt pavements.

Table 2.1. Distresses in asphalt pavements

Distress	Description
Water Pumping and Bleeding	Pumping is the ejection of fine material and water from the bottom layers using cracks in the asphalt layer under moving loads is known as pumping. On the other hand, water bleeding occurs when water uses porous asphalt layers to enter/seep into cracks and joints.
Rutting	It can exist in the form of either subgrade or mixed rutting. The former occurs when the loading causes the formation of wheel path depressions, while the latter appears as a result of the formation of wheel path depressions without the subgrade rutting.
Potholes	These are either tiny or medium bowl-shaped depressions that develop on the pavement surface and extend down to the pavement's course
Slippage Cracking	Crescent-shaped cracks generally with two ends pointed into the direction of traffic.
Wheel Path and Non-Wheel Longitudinal Cracking	Exists in the form of either wheel path and non-wheel path longitudinal cracks. Both are always parallel to the pavement's centreline, but the former occurs in the wheel path while the latter occurs outside the wheel path.
Joint Reflection Cracking	Cracks are formed right on top of the rigid pavement joints.
Block Cracking	It can occur anyway along the road irrespective of whether the area is traffic or non-traffic area and often range in size from 0.1 m ² to 9 m ² notable examples include transverse and longitudinal cracking.
Transverse Cracking	It is a form of thermal cracking that forms in a laydown direction that is perpendicular to the pavement's centreline.
Fatigue Cracking	It occurs when repeated traffic loading causes a chain of interconnected cracks.
Patch Deterioration	These are defects that occur in a repaired pavement area.
Depression	Localized pavement surface areas with slightly lower elevations than the surrounding pavement

Shoving	It occurs when HMA abuts a rigid object due to the formation of short waves.
Corrugation	Relatively similar to shoving but occurs perpendicularly, and it is caused by ripples.
Bleeding	It is a sticky film of asphalt binder that occurs on the pavement surface.
Edge Cracking	These are found at a distance of 0.6 m off the pavement edge and exist in the form of crescent-shaped cracks. Notable examples include longitudinal cracks.
Polished Aggregate	These are non-angular and small particles that are found on top of the asphalt binder and occur in an HMA pavement area.

2.5.2. Condition indexes

Several benefits of using condition indexes like the PCI are well documented in various studies. In a related study by (Staniek, 2018), it is highlighted that the road pavement condition index offers insights into the present condition of road pavements. Elhadidy et al. (2021) tied the benefits of road pavement condition indexes to effective road development and maintenance strategies. Finally (Marcelino et al., 2018) assert that better and contemporary road networks capable of performing better and lasting longer are devised on a solid platform of acceptable road pavement condition indexes.

Leiva-Villacorta et al. (2017), document the benefits of applying road pavement condition index to acquire information concerning asphalt road pavements' structural and serviceability indicators and surface distresses. As a result, (Leiva-Villacorta et al., 2017) suggested that it is instrumental in examining the road distress type, severity, and density to determine the overall PCI. Regarding the same issue, (Elhadidy et al., 2021) underscore the importance of using master curves. Both approaches are vital and contribute towards the development of acceptable asphalt pavement PCI and effective RMS.

Nevertheless, there are various distinct road pavement PCIs. Each PCI has its specific guidelines related to its goals and strategic capabilities to ascertain and deal with road distress and its type, severity, and density. A list of some of the kinds of condition indexes, their related methods, and distresses are provided in Table 2.2.

Table 2.2. Examples of asphalt PCIs

	PCIs	Method	Surface Deterioration	Patching and Potholes	Cracking	Roughness/ Ride Quality	Other Distresses
1	PCI (ASTM, 2008)	Master Curves	Swell Corrugations Depressions Raveling Polishes Bleeding Shoving Rutting	Potholes Deterioration Patch	Transversal Edge Block Fatigue	Ride Quality	Railroad crossing Shoulder drop-off Sags and bumps
2	Pavement Quality Index (Haas et al., 1994)	Expert Panel Evaluation	Surface Distress Index (SDI)	SDI	SDI	Riding Condition Index	-
3	Pavement Condition Index (Dictuc, 2006)	Structural Adequacy Index	Bleeding Rutting	Potholes	Linear Fatigue	IRI	-

4	Present Serviceability Index (AASHTO, 1993)	Structural Adequacy Index	Rutting	Patched surface	Cracked surface	Variance Slope	-
5	Serviceability Index (MINVU, 1999)	Structural Adequacy Index	Rutting	Patched surface	Cracking Index	Ride quality	-

2.6. The Significance of Cement Stabilisation in Road Pavements

Vast stabilization methods have been devised to enhance the strength of weak soil materials or bases. As a result, stabilizers like cement, fly ash, asphalt emulsion, and lime have been devised for such purposes (Arulrajah et al., 2020) contend that the importance of such stabilizers is significantly evident in academic studies highlighting that stabilizers are essential for improving recycled materials' mechanical properties as a subbase or base courses in pavements. Meanwhile, research on recycled and reclaimed materials is going, and much is needed to explore ways of developing cost-effective and durable courses in pavements.

Meanwhile, there are concerns regarding the use of cement as a stabilization agent. For instance (Kasu et al., 2020) assert that various types of cement have distinct stabilization effects or contributions. This is relatively true and aligns with (Taha et al., 2002) suggestions highlighting that cement properties are the key that influences cement's stabilization effects. As a result, various forms of types of cement-like CEM IV 32.5R (Xuan et al., 2012) and (Behiry, 2013) have been noted to have significantly different stabilization effects. However, not much has been done, including other cement forms and assessing their effectiveness when used as stabilization agents. Notable examples can be linked to pozzolanic cement, which this study seeks to evaluate its stabilization effects on

RAP. Cement stabilization is considered to be essential because of easy market availability (LaHucik et al., 2016) and the ability to enhance rapidly strengthened materials (Faysal et al., 2016).

Studies highlight that cement stabilization of RAP produces a RAP material composed of various mechanical properties that must be tested to determine its worthiness. For instance (Saha and Mandal, 2017) contend that stabilized RAP needs to be checked for permeability to ensure that it does not get saturated with moisture that damages the pavement. Besides, other essential features like pavement's service life (Mousa et al., 2021) and saturation (Katte et al., 2019) have to be assessed to determine the effectiveness of the stabilization method. Various testing methods have been devised for such purposes and can assess the required performance attributes. These include modulus of elasticity, indirect tensile strength, and unconfined compressive strength.

Cement stabilization can be applied in different contexts for different purposes (Zang et al., 2019) outlined that glass, slag, and red mud can be stabilized using cement and utilized as a base in pavements. Other studies outlined that cement stabilization plays a vital role in electrolyte manganese residue production plants to process industrial waste and several hazardous waste materials (Arshad, 2020; Kasu et al., 2020). Goals like stiffness and strength are also presumed to be essential outcomes of cement stabilization (Arulrajah et al., 2020).

Extensive empirical studies are documenting the usage of cement in pavement construction, and the activities to which it is put to are vast as well (Chakravarthi et al., 2019; Faysal et al., 2016; LaHucik et al., 2016; Xuan et al., 2012). Sound barriers, pavements, safety barriers, tunnels, and bridges are critical areas where cement stabilization can be applied. Additionally, the related benefits encompass lower deformation under loads, increased stiffness, and high bearing capacity that are attained as a result of treating bases with cement. The various construction fields in which cement stabilization is applied are cell-filled pavements, construction of interlocking block

pavement and concrete pavement, debonding layer over stabilized cemented bases, heavy-duty industrial floors, Airports runway take-off, taxiway, and parking aprons, recycling of pavement with treated subbases, and bases, etc.

The importance of cement stabilization has been well documented in academic studies but with different angles of focus and the application of distinct examinations methods. Notable studies can be linked to (Taha et al., 2002) insights, showing that conventional bases are ineffective when used to stabilize RAP-virgin aggregate mixes compared to cement stabilization. Subsequent studies illustrated that this is conditional to the applied cement content (Xuan et al., 2012). This entails that using inappropriate cement contents affects a base's modulus and strength. The study findings demonstrated a decline in the base's modulus and strength following an increase in the cement content. Similar results were made by (Behiry, 2013), who noted that dry density, curing time, and cement content tend to affect the performance of cement-treated recycled materials. The effects of other influencing conditions like freeze zones were noted in a study by (LaHucik et al., 2016), which demonstrated that bases with quarry by-products and RAP in freeze zones could be stabilized by cement on a small scale.

Faysal et al. (2016), conducted a study to analyze the performance of bases when stabilized with cement. They noted that the bases' stiffness and strength features are well enhanced following the addition of specific proportions of cement contents.

Chakravarthi et al. (2020), conducted a study to analyze cement applications in pavement engineering. They pointed out that the increased use of recycled materials like RAP in pavements does not always meet the required mechanical specifications. Hence, they suggested that cement stabilization of RAP should be used to rectify such issues. This also aligns with (Yan et al., 2020) suggestions denoting that pavements tend to deteriorate because of changes in traffic and environmental conditions experienced during their service life. Additionally, the highlighted that using stabilized RAP is beneficial for constructing road pavements because it can be utilized in different pavement proportions

and layers. This places a significant demand on the need to execute this study to verify whether the mentioned benefits are practically attainable.

Though several ideas can be deduced from vast empirical sources addressing matters related to the use of recycled aggregates in pavements, limitations caused by inferior mechanical and physical properties are significant issues of concern. The same observations were made in (Yu-Shan and Shakiba, 2021) study that depicts the adverse effects of RAP on the pavement's strength. In another study by (Seferoglu et al., 2018), it is observed that pavements formed by RAP suffered serious deformation problems. Mousa et al. (2021) noted that not all pavements made from RAP are durable. Other issues such as poor distribution of stresses are also considered to be of huge concern when using reclaimed asphalt (Chakravarthi and Shankar, 2021; Kasu et al., 2020; Ramzi et al., 2020). All these observations demand a solution capable of addressing such concerns leading to improved RAP performance. As such, several studies recommend that stabilization methods be applied (Arshad, 2020; Chhabra et al., 2021; LaHucik et al., 2016; Yan et al., 2020). Most importantly, cement stabilization must be considered desirable for such purposes (Arulrajah et al., 2020; Faysal et al., 2016; Xuan et al., 2012).

Saha and Mandal (2017), assert that recycled materials' properties are improvable either by blending with superior quality materials or adding additives. Observations made in such examinations revealed that there were substantial improvements in pavements life after going through a cement stabilization process. Such modifications result from a reduction in deflections, and hence, it is instrumental in considering that cement stabilization is essential for improving the stiffness of bases. This study aligns with these observations to propose implementing cement stabilization in RAPs to enhance their mechanical features. Chakravarthi et al. (2019), in an attempt to study the performance of mixed portions of recycled concrete pavement bases and RAP, established that cement stabilization offers immense benefits in pavements production. Improvements in bases' stiffness and strength were noted, leading to the conclusion that stabilization significantly improves the performance of bases.

Arulrajah et al. (2020), conducted a study to determine the quantity of cement required to stabilize pavement sub-base and bases containing polyethylene terephthalate found in demolition and construction wastes. Their results showed that pavement sub-base and bases are sufficiently stabilized by a combination of 3% cement and polyethylene terephthalate found in demolition and construction wastes. This implies that various cement types have different stabilize action effects on pavement sub-base and bases. Such is to be observed, especially when newly introduced cement types like pozzolanic cement that is not widely examined in academic studies is introduced and applied in the stabilization of RAP. This concurs with findings made by (Kasu et al., 2020) that examined similar effects concerning the behavior of pavement sub-base and bases when mixed with RAP and cement. They illustrated that both the recycled aggregate contents and durability and mechanical properties are distinctively affected by the application of various cement contents.

The importance of reducing stress and improving the mechanical properties of RAP is evidenced in a study conducted by (Arshad, 2020). Arshad demonstrated that cement contents ranging from 1.5% to 4.5% tend to significantly reduce strains occurring in recycled aggregate blends and improve their mechanical properties. This implies that there is a certain amount of cement required to ensure that RAP is sufficiently and effectively stabilized. Thus mixing any random cement content will not yield the required results. The effects of stabilizing bases and sub-bases with other materials different from cement are also documented in civil engineering. For instance, a study by (Yan et al., 2020) focusing on studying the performance of open-graded cement stabilized macadam containing recycled aggregate showed significant changes in bases containing demolition and construction waste concerning their durability and mechanical properties. Improvements in the bases' performance were noted to average 30%, which is significant in pavement management. Hence, this underscores the importance of pavement stabilization in civil engineering.

Studies have been extended to explore the benefits the cement stabilization when applied in different contexts. For instance (Ramzi et al., 2020) outlined that road subbases and bases can be stabilized with cement and provide the required benefits. As such, their established findings depicted that there were considerable improvements in road pavements' stiffness and strength when stabilized with cement. In another related study (Chhabra et al., 2021) demonstrated substantial improvements in the performance of cement-treated base layer when combined with road bases and subbases and RAP material. Finally (Chakravarthi and Shankar, 2021) illustrated similar effects and concluded that cement stabilization is vital for improving the performance of RAP material. Hence, it is in this context that this study argues that similar improvements in RAP are potentially observable in Erbil, Iraq when RAP is stabilized with pozzolanic cement. Table 2.5 summarizes related studies about the potential benefits of cement stabilization.

Table 2.3. Summary of potential benefits of cement stabilization

Author(s)	Deductions
Taha et al. (2002)	Conventional bases are not practical when used to stabilize RAP-virgin aggregate mixes compared to cement stabilization
Xuan et al. (2012)	The study findings demonstrated a decline in the base's modulus and strength following an increase in the cement content.
Behiry. (2013)	Noted that dry density, curing time, and cement content tend to affect the performance of cement treated recycled materials
LaHucik et al. (2016)	Demonstrated that bases with quarry by-products and RAP in freeze zones can be stabilized by cement on a small scale.
Faysal et al. (2016)	Noted that the bases' stiffness and strength features are well enhanced following the addition of specific proportions of cement contents.
Chakravarthi et al. (2019)	Established that cement stabilization offers immense benefits in pavements production. Improvements in bases' stiffness and strength were noted, leading to the conclusion that stabilization significantly improves the performance of bases

Yan et al. (2020)	Open-graded cement stabilized macadam containing recycled aggregate bases containing demolition and construction waste significantly performs better by 30%. Additionally, this improved the bases' durability and mechanical properties.
Arshad (2020)	Cement contents ranging from 1.5% to 4.5% tend to significantly reduce strains occurring in recycled aggregate blends and improve their mechanical properties.
Kasu et al. (2020)	Illustrated that both the recycled aggregate contents and durability and mechanical properties are distinctively affected by the application of various cement contents.
Arulrajah et al. (2020)	Pavement sub-base and bases are sufficiently stabilized by a combination of 3% cement and polyethylene terephthalate found in demolition and construction wastes.

2.7. Related Studies

The quest to improve the performance of pavements has long been a significant concern. As such, studies have been trying to find ways to find the best ways of using RAP in pavements. For instance (Kazmee et al., 2017) conducted a study to identify ways of using accelerated pavement testing to evaluate reclaimed asphalt pavement materials for pavement unbound granular layers. It was noted that mixtures containing a 40% blend of RAP materials and recycled concrete aggregate exhibited sound improvements in subgrade performance. Additionally, wheel-load rutting during trafficking and deformations during paving were observed to be prominent among base/subbase layers consisting of 100% RAP. Thus, their findings imply that RAP has inherent base or subbase performance-enhancing features capable of improving the performance of road pavements.

Saha and Mandal (2017), demonstrated that the effects of using RAP as a base course on the flexible pavement are influenced by mixing with crushed stone aggregates stabilizing with cement. Significant observable changes in soaked CBR values ranging from 20% to highly above 100% were recorded, while unsoaked CBR values remained

unchanged. Inferred insights into such examinations revealed that RAP could be effectively combined with crushed aggregates to significantly enhance the performance of bases and sub-bases when stabilized with cement. Thus, the importance of stabilizing the mixtures with pozzolanic cement in this study is empirically justifiable. Arshad and Ahmed (2017) conducted a relatively similar study, emphasizing the possibility of using RAP and recycled concrete aggregate in base or subbase layers of flexible pavements. However, relatively different results show that an increase in the RAP content increases accumulative strains. Such effects were also observed in a study by (Mohammadinia et al., 2017) aimed at analyzing the effects of fly ash on properties of crushed brick and reclaimed asphalt in pavement base/subbase applications. That is, high alumina crystalline and silica contents reduce the strength of flexible pavements. This is because of the deterioration of the soil structure matrix, and similar effects are most likely to be observed with asphalt pavements. This entails that further examinations are required to determine the optimal combinations of RAP and aggregate mixtures that can optimally enhance the performance of asphalt pavements as intended by this study.

Imtiaz et al. (2020), conducted a study on recycled base and sub-base materials' strength characterization and microstructure. The intention was to illustrate the positive benefits derived from applying RAP as a base or subbase. It was demonstrated that RAP reduces unconfined compressive strength by enhancing the number of pores in the mixture. Relatively similar benefits are most likely to be observed when the asphalt is brought into consideration, and such will be the focus of this present study.

Various methods of testing RAP and crushed aggregates mixtures also exist, but concerns are raised about the results' distinctiveness. For example (Ungureanu et al., 2020) applied an accelerated testing method to assess the performance of a recycled road structure combined with RAP materials. They showed that there are some insignificant changes in the performance of a recycled road structure combined with RAP materials. On the other hand (Costa et al., 2020) examined sustainable pavement base layers using reclaimed asphalt aggregates and cementitious binders. The sustainability of such

pavements was noted to be considerable, and this questions the extent to which test methods influence the quality of the established results. In this regard, this study will apply the CBR, constant head permeability test, and the modified proctor test to enhance the quality of the results established from the RAP and crushed aggregate mixture stabilized with cement.

Paotong et al. (2020), used Natural Rubber Latex (NRL) to demonstrate that RAP's features can be enhanced to improve pavement performance. Their findings arguably showed that a 5-15% NRL modified RAP mix stabilized with 3-7% cement possessed the required properties that met the stated Thailand highway engineering standards. In such cases, RAP was viewed as having substantial environmental and economic benefits. However, due to limitations linked to NRL use, this study proposes that better results are obtainable when the asphalt is used, and such is to be proved.

Another study by (Cakuru et al., 2021) that uses the General Specifications for Roads and Bridges demonstrated that 45 and 50% of RAP could satisfy the G30 material properties required for subbase layers in Uganda. Such findings imply that optimizing is of enormous concern when dealing with matters involving the use of RAP. However, such needs to be explored in the context of Iraq as limited studies are examining these issues in Iraq. Moreover, the goal will be to assess the desired optimal conditions suitable for the Iraq climatic conditions.

It is demonstrated in (Mousa et al., 2021) study that using RAP as base/subbase material does not always lead to improved pavement performance in Egypt. The results showed that additional RAP materials added to the blend had an adverse effect on permeability and a positive effect on resilient modulus. Given that pavement, performance is measured using various aspects like stiffness, moisture context, permeability, the effects of using RAP as base/subbase material are questionable. Thus, this study seeks to address such concerns by applying CBR and permeability tests to investigate relatively similar issues in Iraq.

Reviewed insights provided in this chapter show that the application of RAP as a base/subbase material is beneficial but not void of adverse effects on other pavement features. As such, they are using RAP in pavements enhances the performance of certain pavement elements and compromises the performance of other elements. It has been inferred from such examinations that RAP-crushed aggregates blend have to be optimally mixed in the right proportions to enhance the performance of asphalt pavements. Additionally, the positive benefits of such actions are enhanced by stabilizing the mixtures with cement. Thus, the goal of the next chapter will be to explore ways through RAP; crushed aggregates stabilized with cement can be optimally mixed to enhance the performance of asphalt road pavements in Iraq.

3. MATERIAL and METHOD

3.1. Introduction

This chapter is dedicated to the examination of methods used to address empirical matters related to the use of reclaimed asphalt pavement and crushed aggregate to improve the road bases and subbases. As such, the applicability and effectiveness of materials and experimental methods used was guided by the need to answer the following research questions:

- Is there a possibility of using Reclaimed Asphalt Pavement together with crash aggregate to improve the performance of the base course layer? If so, then how can high-quality crushed aggregate materials and/or adding chemical stabilizing agents (cement) be utilized to strengthen RAP as a component of road base courses?
- What are the best optimal RAP/Crash aggregate and chemical stabilizing agent combinations capable of effectively enhancing the quality and performance of the base course layer with regards to:
 1. The bearing capacity.
 2. Permeability capability.
- Is the selected optimal RAP-crash aggregate combination suitable for use in Iraq?

In light of the inquiries mentioned above, this chapter looks at the study area concerning its location and climate conditions and how they affect road conditions and performance in Erbil, Iraq. The state of the road's conditions was separately examined to determine the concerned road distress types and severity to ascertain how effectively RAP, crushed aggregates, and the cement will be used to improve the road's conditions and

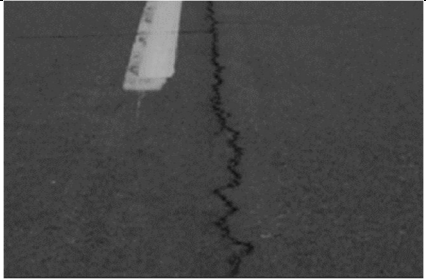
performance. Consequently, this chapter also examined the materials used in performing the experimental procedures (RAP, crushed aggregates, and cement), experimental methods (the modified proctor test, the soaked CBR test, and constant head permeability test), and data analysis procedures that encompassed regression analysis and optimization tests.

3.2. Study Area

The study was conducted in Erbil, Iraq. Specific attention was devoted to Ankawa road because this road is affected by various road distresses like potholes, rutting, longitudinal cracking, alligators cracking, slippage cracking, block cracking, as shown by Table 3.1. Table 3.1 also provides a graphical illustration of such road distresses found along Ankawa road in Erbil and their related severity levels established by the researcher during the field study.

Table 3.1. Types of road distresses found along the Ankawa Roads

No.	Road distress	Graphical presentation	Severity
1.	Potholes		<i>H= High severity (Any crack with a width > 1.905cm); M=Medium severity (Any crack with a width > 0.635cm) L=Low severity (An unsealed crack with a width ≤ 0.635cm)</i>
Potholes found along the Ankawa road are caused by subsidence or wear that results in the formation of hollows or depressions on the road surface (Akyildiz, 2008). Potholes found along the Ankawa road have a high deduct value of 96 and distress density of 100%			

2.	Rutting		H= High severity (Any crack with a width > 1.905cm); M=Medium severity (Any crack with a width > 0.635cm) L=Low severity (An unsealed crack with a width $\leq$ 0.635cm)
Cases of rutting distress are also evident along Ankawa road and have a high severity deduction value of 90%, medium severity deduction value of 76%, and a low severity deduction value of 50%.			
3.	Alligator cracking		H= High severity (Any crack with a width > 1.905cm); M=Medium severity (Any crack with a width > 0.635cm) L=Low severity (An unsealed crack with a width $\leq$ 0.635cm)
Alligator cracking problems are observable with high severity distress of 96%, medium and low severities of 78%, and 66%, respectively. This is because the Road does not have a good asphalt surface.			
4.	Longitudinal cracking		H= High severity (Any crack with a width > 1.905cm); M=Medium severity (Any crack with a width > 0.635cm) L=Low severity (An unsealed crack with a width $\leq$ 0.635cm).
Longitudinal cracking was also noted to be a prevalent feature found along Ankawa road, with the longest crack that measured up to 138.20 meters long.			
5.	Slippage cracking		H= High severity (Any crack with a width > 1.905cm); M=Medium severity (Any crack with a width > 0.635cm) L=Low severity (An unsealed crack with a width $\leq$ 0.635cm)

Ankawa road also suffers from slippage cracking problems caused by turning wheels and braking by motorists driving along the road. This eventually results in road surface deformations known as slippage cracking. The measured slippage cracks had a high severity deduct density value of 94%, medium and low severity values of 54%, and 40%, respectively.

6.	Block cracking		H= High severity (Any crack with a width > 1.905cm); M=Medium severity (Any crack with a width > 0.635cm) L=Low severity (An unsealed crack with a width ≤ 0.635cm)
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According to the researcher's observations, it was observed that Ankawa road had interconnected rectangular cracks known as block cracks. These cracks ranged in size from 0.3 x 0.3 m to 3 x 3 m. in overall, the severity of the block cracking distress was considered to be relatively high, and the same applies to both the medium and low rigors, which averaged 82%, 52%, and 29%, respectively.

Erbil is situated in northern Iraq between latitudes 35°30' and longitudes 43°22' and 45°05E and borders Kuwait, Saudi Arabia, Jordan, Syria, Turkey, and Iran (see Figure 3.1).



Figure 3.1. Geographical map of Erbil

There was an estimated 1.5 million people living in Erbil in 2020, up from the recorded 2018 total of 821 000 people (Macrotrends, 2021). Therefore, (Mandal et al., 2020) consider that the conditions of road pavements are deemed to be affected by the volume of traffic passing through that particular place.

Mahmood and Al-Salih (2018), hinted that it is imperative to consider that Iraq is classified as a hot climate area as it lies with the part of the Middle East region. Such a distinct observation is vital as it influences Erbil's weather conditions, such as asphalt road conditions and performance. As a result, the climate consult program was used to determine Iraq's weather conditions for 2021, and the results are shown in Figure 3.2.

Figure 3.2 shows extreme temperature conditions experienced between June and August with temperatures exceeding 48°C . On the other hand, the winter period commences in November (winter lasts up to April) and sees temperatures dropping to as low as 0°C . Thus, the extreme temperature conditions can cause distinct and significant expansion and contraction effects leading to strains that cause road failure. Hence, this supports the important reasons why Ankawa road in Erbil, Iraq, has several forms of road distress.

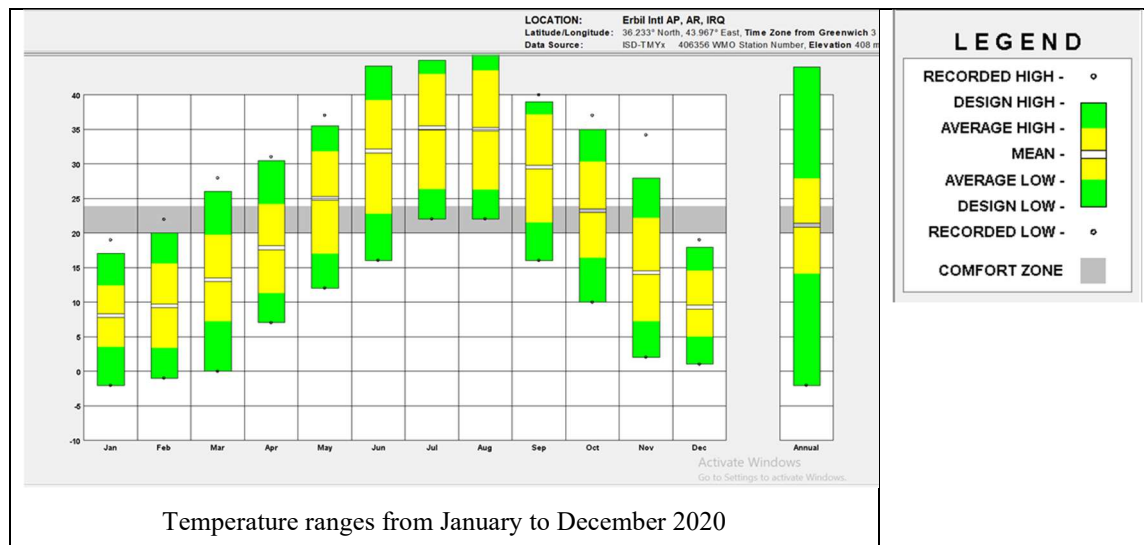


Figure 3.2. Climate consultant temperature ranges for the Erbil

3.3. Materials

Efforts to determine the uses of reclaimed asphalt pavement blended with crushed aggregates to improve the base or sub-base layers of roads required Reclaimed Asphalt Pavement (RAP) (see Figure 3.3), crushed stone aggregates, and cement. Each of these materials plays a vital role in improving the RAP's properties such as density, strength, bearing capacity, and permeability. Additionally, they were crucial for applying the required and related experimental methods, leading to reliable findings to answer the suggested research questions.



Figure 3.3. RAP Materials

3.3.1. Reclaimed asphalt pavement

Empirical ideas provided in the previous chapter (literature review) reviewed that Reclaimed Asphalt Pavement (RAP) refers to reprocessed and/or removed pavement materials composed of aggregates and asphalt (Federal Highway Administration, 2016). In this study, the primary material used is high-quality graded RAP that was crushed and screened to produce well-graded aggregates coated with asphalt cement.



Figure 3.4. RAP Milling along Ankawa road in Erbil, Iraq

The RAP was scraped by milling machines from on roads and directly mixed with CA and Cement. The RAP was obtained from an Erbil-Ainkawa roads milling project based in KRI (see Figure 3.4).

3.3.1.1. Mechanical properties

RAP's mechanical properties have been established as being influenced by (1) the extent to which the RAP has been prepared for specific application, (2) methods utilized in recovering the materials, and (3) the original asphalt pavement type (Highway Federation Administration, 2016). For instance, an increase in the RAP's unit weight is presumed to reduce the compacted unit RAP's weight (Highway Federation Administration, 2016), and this has been linked to maximum dry density values of 1600 kg/m^3 to 2000 kg/m^3 (Senior et al., 1994). On the other hand (Valdés et al., 2011) made prior examinations revealed that RAP materials composed of trap rock aggregate have California Bearing Ratio (CBR) values ranging from 20% to 25%. Nevertheless, higher CBR values exceeding 40% are obtainable when the RAP's effect has been strengthened by applying cement blended with natural aggregates for use in granular bases (Hassan et al., 2021).

3.3.1.2. Physical properties

RAP's physical properties are distinctively different from other materials because of features like asphalt concrete mix (binder course, wearing surface, etc.). Furthermore, a considerable difference can exist between asphalt concrete mixes because of features like consistency, size, and aggregate quality differences (Hassan et al., 2000). According to the (Highway Federation Administration, ww2016), the aggregates must have acceptable friction resistance characteristics and be polished so that they can withstand abrasion or wear. However, it is vital to establish that aggregate degradation is bound to occur because of the crushing and milling process. Shirodkar et al. (2011) noted that such degradation differs between virgin aggregates and milled aggregates. This concurs with (Copeland, 2011) examinations showing that the degradation of virgin aggregates is less dense and rough compared to that of milled aggregates.

Further examinations were made to analyze the influence of particle size distribution on the produced RAP. For instance (McDaniel et al., 2002) contend that crushed or milled RAP have different particle size distributions. Similar findings were made by (Pradyumna et al., 2013). Still, the nature of equipped utilized in producing the RAP plays a crucial role in determining the crushed or milled RAP's particle size distribution. Table 3.2 shows the resultant particle size distribution ranges produced from RAP's crushing or milling process. A study by (Valdés et al., 2011) highlights that all produced RAP has a maximum allowable size of 51mm and is crushed or milled down to 38mm.

Meanwhile, the RAP's moisture content and aggregates' types influence the processed or milled RAP's unit weight. However, available studies do not provide many details regarding the processed or milled RAP's unit weight. Still, a standard weight of 1940 to 2300 kg/m³ is considered suitable though it is relatively lower than natural aggregates' unit weight (Pradyumna et al., 2013). Table 3.2 provides a summary of the RAP's mechanical and physical properties.

Table 3.2. Summary of the RAP's mechanical and physical properties (FHART, 2018)

Type of Property	RAP Property	Typical Range of Values
Mechanical properties	CBR	100% RAP: 20-25%
	Compacted Unit Weight	1600 - 2000 kg/m ³
Physical properties	Absolute Viscosity or Recovered Asphalt Cement	Standard: 10-80 at 25°C
	Asphalt Content	Maximum Range: 3-7% Average: 4.5-6%
	Moisture Content	Maximum: 7-8% Average: up to 5%
	Unit Weight	1940 - 2300 kg/m ³

3.3.1.3. Chemical properties

Shirodkar et al. (2011), study noted that about 93% to 97% of the RAP's weight is composed of mineral aggregates, and 3% to 7% of the remaining weight is made up of hardened asphalt cement. Nevertheless, limited quantities of polycyclic, nitrogen, and Sulphur and large amounts of high molecular weight aliphatic hydrocarbon compounds were also found to exist in RAP cement. Additionally, oils and resins (maltenes and asphaltenes) combinations exist as part of asphalt cement.



Figure 3.5. Sieve Analysis of milled RAP

Sieve analysis was conducted using milled RAP with an average bitumen content of 4.6 percent by weight of the mix after rotary separation following ASTM D6307-16 (see Figure 3.5). The fracture ratio of particles retained on sieve number 4 was 100%, and 34% of the RAP was sieved for every 200 passing sieves when the specification limit was set to more than 75%. In addition, the non-liquid limit and non-plastic index were conducted during the testing, with a CBR of 49.7% at 95% compaction. Furthermore, the reported sieve analysis results reported in (Table 3.3) show that there is a directly proportional relationship between the sieved RAP particle sizes and the specification limit (Highway Federation Administration, 2016; Senior et al., 1994).

Table 3.3. RAP material's Particle size distribution and physical tests

Sieve analysis ASTM C136-06 (percentage passing)			
Reclaimed asphalt material			
mm	inch/no.	test results	spesification limit
38	1 1/2	100	100
25	1	99	80-100
19	3/4	95	-
12.5	1/2	83	50-80
9.5	3/8	71	-
4.75	no. 4	40	30-60
2.36	no. 8	33	-
0.425	no. 40	7	10 _ 30
0.075	no. 200	2.4	5 _ 12
passing sieve no.200/ passing sieve no. 40 (%)		34	≤ 60
fracture ratio of particles retained on sieve no. 4 (%)		100	≥ 75
MDD (gm/cm3)	ASTM D1557-12	2.133	-
OMC (%)	ASTM D2216-05	4.7	-
CBR at 95 % compaction (%)	ASTM D1883-07	49.7	-
Liquid limit (%)	ASTM D4318-05	N.L.L	≤ 25
Plasticity index (%)	ASTM D4318-05	N.P.L	≤ 4
Bulk spesific gravity	ASTM C127-07	2.451	-
Asphalt content %	ASTM D6307-16	4.6	-

3.3.2. Crushed stone aggregates

Crushed Stone Aggregates (CSA) were used in this study to strengthen the RAP (Seferoglu et al., 2018). Previous studies acknowledge the importance of combining RAP with CSA, citing that there are pivotal for pavement rehabilitation and strengthening purposes (Saha and Mandal, 2017; Seferoglu et al., 2018). In addition, CSA was essential for use in this study because they are cost-effective compared to wet mixed macadam (Saha and Mandal, 2017). Consequently, the RAP was blended with 20%, 40%, 60%, 75%, 90% and 100% proportions of the CSA. After that, the Modified Proctor test (Optimum Moisture Content (OMC), and Maximum Dry Densities (MDD)), California bearing ratio (CBR) test, and Constant head permeability test was applied to examine the resultant combined aggregates' density, bearing, strength, and permeability, respectively.

Table 3.4. Crushed aggregate's particle size distribution and physical tests

Sieve analysis ASTM C136-06 (percentage passing)			
Crushed Aggregate material			
mm	inch/no.	test results	spesification limit
38	1 1/2	100	100
25	1	93	80-100
19	3/4	84	-
12.5	1/2	70	50-80
9.5	3/8	61	-
4.75	no. 4	46	30-60
2.36	no. 8	27	—
0.425	no. 40	15	10 _ 30
0.075	no. 200	7	5 _ 12
passing sieve no.200/ passing sieve no. 40 (%)		47	≤ 60
fracture ratio of particles retained on sieve no. 4 (%)		82	≥ 75
MDD (gm/cm3)	ASTM D1557-12	2.321	
OMC (%)	ASTM D2216-05	5.5	
CBR at 95 % compaction (%)	ASTM D1883-07	268	
Liquid limit (%)	ASTM D4318-05	N.L.L	≤ 25
Plasticity index (%)	ASTM D4318-05	N.P.L	≤ 4
Bulk spesific gravity	ASTM C127-07	2.732	

Crushed aggregate was collected from Erbil's Gopal Highway project. The primary aggregate used was graded crushed gravel. Laboratory tests were performed, and the particle size distribution and physical tests of crushed aggregate material are shown in (Table 3.4). The required crushed aggregates produced from the sieve analysis had a CBR of 268 at 95% compaction, liquid limit, and plastic index less than or equal to 25% and 4%, respectively. The bulk specific gravity of the sieved CA was 2.73%. In addition, the number 4 sieved CA had a fracture ratio of 82%, and the percentage passing of the crushed aggregates was directly proportional to the specification limit.

Nevertheless, the RAP and crushed aggregate compositions were roughly the same, and there should be slight variation in aggregate qualities (Seferoglu et al., 2018). Table 3.4 also supports the idea that the sieved CA particle sizes and specification limits are directly proportional (Seferoglu et al., 2018).

3.3.3. Cement

The RAP required a stabilizing material, and as such, the study applied Cement. Notably, pozzolanic cement was used for accomplishing such purposes. The importance of using cement as an establishing agent is evident in academic studies (Saha and Mandal, 2017; Seferoglu et al., 2018; Thakur, 2011). Additionally (Seferoglu et al., 2018) consider cement as the best and most effective material for treating the RAP. Therefore, the study used pozzolanic cement instead of other cement forms because pozzolanic cement reduces water evaporation and permeability and increases workability (BPSC, 2012). Additionally, pozzolanic cement offers excellent resistance to expansion and can reduce creep and bleeding (BPSC, 2012). As a result, cement ratios of 1%, 1.5%, 2.5%, and 4% were applied together with the RAP\CA blend and subsequently tested to determine the implications and effectiveness of using pozzolanic cement on the RAP. The samples were left in plastic bags for the curing process at room temperature for 24 hours and seven days.

3.4. Experimental Method

Three experimental methods in the name of the modified proctor test (MDD and OMC), the California bearing ratio test, and the Constant head permeability test was applied in determining the uses of reclaimed asphalt pavement blended with crushed aggregates to improve the base or sub-base layers of roads.

3.4.1. Modified proctor test

The Modified Proctor Test carries much significance in engineering and road construction. Studies highlight that it plays a vital role in determining moisture content in a particular soil specimen (Di Matteo et al., 2009; Seferoglu et al., 2018). This is usually made possible by studying the blends' Maximum Dry Densities (MDD) and Optimum Moisture Contents (OMC).

Meanwhile, other studies pinpoint that the Modified Proctor Test is applied in conditions requiring the examination of optimum compaction in designated areas like turnouts and swabs utilizing heavy compaction tools like a smooth drum or vibration rollers (Duque et al., 2020; Scott et al., 2012). The Modified Proctor Test is relatively similar to the standard compaction test, but the used specimen in a Modified Proctor Test is remolded using modified compaction effort (Shaivan and Sridharan, 2020).

In this study, all the CA, RAP, and cement blends samples were placed in a thermostatically controlled oven for 24 hours to dry at temperatures between 110 ± 5 °C, as shown in (Figure 3.6). The main reason behind this procedure was to determine the CA, RAP, and cement blends' moisture content.



Figure 3.6. Thermostatically controlled oven dry for OMC

Meanwhile, it is crucial to note that Modified Proctor Test has to be carried out under appropriate standards. For example (Khalaf et al., 2020) recommend using the RMS T112 method and Australian Standard AS1289.5.2.1. However, some studies also suggested that reliable and valid results are obtainable when the test is performed following ASTM D1557-12 and ASTM D2216-05 (Saha and Mandal, 2017; Seferoglu et al., 2018). Thus, this study applied suggestions by (Seferoglu et al., 2018) in testing the blended RAP's maximum dry density (MDD) and optimum moisture content (OMC). The CA, RAP, and cement blends were placed in a 6-inch MDD mold and filled into five layers. Then, the layers were compacted using a hammer weighing 4.5 kg (44.48 N) and had a fall of 45.72 cm producing a compaction effort of (2700 kN-m/m³) by using 56 blows per layer. (see Figure 3.7).



Figure 3.7. Compaction testing machine

3.4.2. California bearing ratio test

The next step was to conduct the soaked CBR test. Nevertheless, the CBR test is an essential procedure that is part of site analysis in determining the thickness of materials needed for the proposed road construction (Nini, 2017). In other words, the CBR is used in estimating subgrades and highway subbases' mechanical strength and load-bearing capacity. As a result, the importance of the CBR is now attached to the design of car parks, pavements, roads, and related activities (Nugroh, 2019).

Keys issues concerning the significance of the CBR are highly linked to its performance. For instance (Yildirim and Gunaydin, 2011) assert that the CBR must be well performed under the right conditions and use suitable materials to provide accurate results. Consequently, The initial CBR process, according to this study, is to measure the pressure required to penetrate a soil sample with a standard area plunger. The pressure determined is then divided by the pressure required to achieve equal penetration in normal crushed rock (Nini, 2017). Meanwhile, it is noted that harder surfaces have higher CBR values (Kim et al., 2019). Additionally (Nugroh, 2019) pointed out that a high-quality base has maximum CBR values ranging between 86% and that certain sand soils have CBR values of about 10%, while that of clay is presumed to be 4%.

The other notable condition about the CBR test is the size of the particles involved. This aligns with (Talukdar, 2014) suggestions citing that the CBR test provides reliable results when used to test soils with particle sizes not exceeding 20mm. Thus, it is encouraged to apply other different tests when testing particle sizes greater than 20mm (Kate et al., 2019). This is evident in (Kim et al., 2019) study, denoting that the Plate Bearing Tests are highly suitable for soil particle sizes exceeding 20mm.

Apart from particle, studies consider ASTM standards when conducting CBR examinations (Ayebale and Bawa, 2019; Hassan et al., 2021; Schlögel et al., 2020). In this regard, this study carried out CBR examinations in line with propositions given by ASTM

D 1883-07 (Standard Test Method). This was applied to all the blended crushed aggregates, RAP, and stabilized RAP. The remolded specimen was prepared by dynamic compaction or static compaction at Proctor's maximum dry density and maintained at optimum moisture content. The applied material exceeded 20 mm I.S. sieve and was retained on a 4.75 mm I.S sieve.

The blended CA, RAP, and cement samples were then placed in plastic bags for curing. All the samples were subject to a curing process for one day and seven days. Figure 3.8 shows the curing process that was done by placing the samples in plastic bags to prevent the evaporation of water.



Figure 3.8. Curing for one day and seven days

The cured CA, RAP, and cement blends were submerged into a soaking water tank at a temperature of 24 °C for 96 hours. Then took off the molds from the soaking tank for testing by the CBR test loading machine to determine their CBRs (see Figure 3.9).

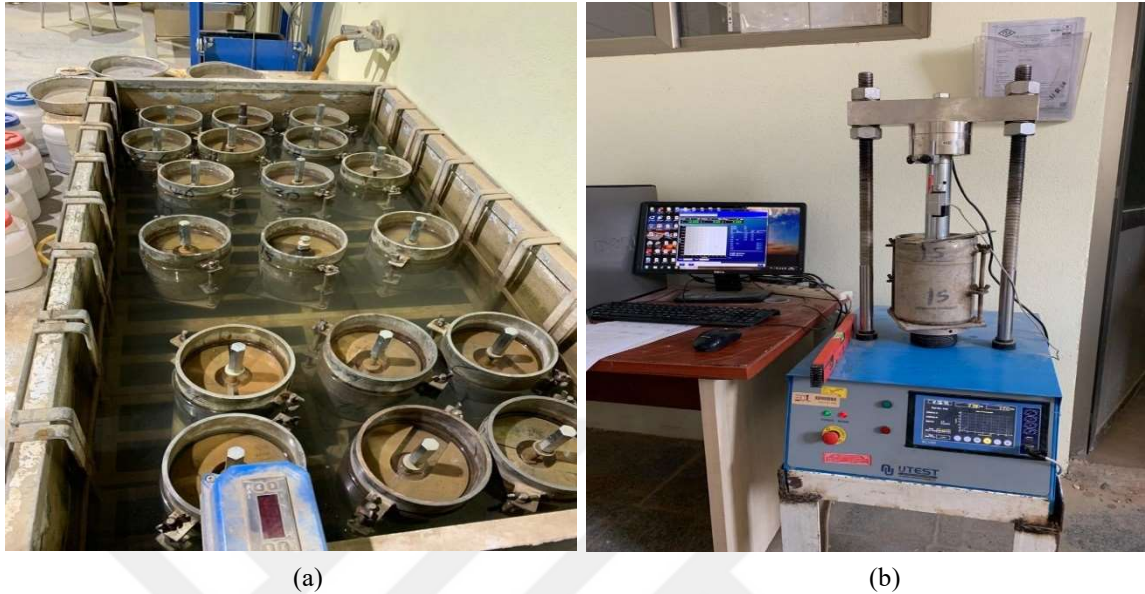


Figure 3.9. CBR test (a) soaking tank for CBR samples (b) CBR loading machine

3.4.3. Constant head permeability test

The study applied the constant-head method to determine the permeability of the RAP in line with the ASTM D 2434 guidelines used in testing the permeability of granular soils (Wu et al., 2012). The constant head method was conducted as follows:

3.4.3.1. Soils samples preparation

Cement and RAP\CA blends were thoroughly mixed with the soil samples and compressed into thin four equal layers of 20.3 mm high above the upper manometer outlet using a permeability cylinder. A 200 mm distance was kept between the upper manometer outlet and the bottom of the permeameter outlet is 200 mm.

3.4.3.2. Permeability test procedures

The laminar flow region was established by saturating the samples and conducting repeated test runs increments of the 0.5cm head. The deviation of the association between

the hydraulic gradient and velocity results in the commencement of the turbulent flow condition. The implications of percentage RAP changes on permeability were carried out in the laminar flow region based on the coefficient of permeability that is determined as follows by (Darcy, 1856) law.

$$K = \frac{QL}{Ath} \quad (1).$$

Where:

K = coefficient of permeability (cm/s),

Q = quantity of water discharged (cm³),

L = distance between manometers

A = cross-sectional area of the specimen,

t = total time of discharge (sec), and

h = difference in head-on manometers (cm).

Existing studies reckon that permeability is a vital base course material parameter because it enhances pavement service life (Mousa et al., 2021; Saha and Mandal, 2017). Besides, it has been noted that pavements are posed deteriorate rapidly when the base course is saturated (Katte et al., 2019). Other studies also concurred with this observation and highlighted that the RAP could suffer additional damages when it traps moisture (Duque et al., 2020; Khalaf et al., 2020; Wu et al., 2012).



Figure 3.10. The applied permeability test device

Concerns were raised about whether the permeability of RAP mixtures is affected by an increase in the quantity of the RAP added to the mixture (Hassan et al., 2021). Hence, it is essential to account for gradation, soil type, and compaction factors. Therefore, in this study, the base course material and RAP specimens' permeability were determined using a constant-head permeameter tests shown by Figure 3.10.

The RAP\CA blend materials used in this study were chosen according to their typical gradation and subjected to constant head permeability examinations according to ASTM D 2434 specifications. Less than 10% of the particles passed through the 75- μm sieve. Following that method and prior to compaction, particles retained on the 19-mm sieve were selected.

It is vital in civil engineering to ensure that the used soil samples have the required permeability standards to improve the quality and performance of the developed structures. Thus, specific ranges have been designed to gauge the permeability of classes of soils. That is, the lower limit and upper limit coefficients of permeability (K in m/s) for impermeable soil are 1×10^{-11} and 5×10^{-7} ; semi-permeable soil 1×10^{-11} and 1×10^{-5} ; and 2×10^{-7} and 2×10^{-1} for permeable soil as shown in Table 3.5.

Table 3.5. Soil permeability classes for civil engineering (FAO, 2021)

Soil permeability classes	Coefficient of permeability (K in m/s)	
	Lower limit	Upper limit
Impermeable	1×10^{-11}	5×10^{-7}
Semi-permeable	1×10^{-11}	1×10^{-5}
Permeable	2×10^{-7}	2×10^{-1}

As a result, the following specific coefficients of permeability are required for all existing soil types used for civil engineering purposes. In such cases, coarse and medium sands have better coefficients of permeability compared to silt clay, clayey silts, dense

silts, fine sands, loose silt, coarse and medium sands and, thus, giving them good drainage properties. Clean gravel possesses good drainage properties (see Table 3.6).

Table 3.6. Typical values of coefficients of permeability (Khatun, 2017)

No.	Soil type	Drainage properties	Coefficients of permeability
1	Coarse gravel	Very good	Exceeds 10^{-1}
2	Sand, clean	Medium	10^{-1} to 10^{-3}
3	Sand, dirty	Low	10^{-3} to 10^{-5}
4	Silt	Very low	10^{-5} to 10^{-7}
5	Clay	Impervious	Less than 10^{-7}

3.5. Data Analysis Procedures

A series of OMC, MDD, CBR, and permeability tests were used to produce the required data that was used in determining the relationship between the quantity of the RAP, CA, Cement, and such relationships were determined using regression analysis. The study then proceeded to conduct optimization tests of 3 mixes containing RAP, CA, and Cement. The following sections provide detailed insights into the regression analysis and optimization tests carried on the RAP, CA, and Cement mixes.

3.5.1. Regression analysis tests

Regression analysis is a statistical modeling method used to analyze relationships between a dependent variable and at least one independent variable (Ngo et al., 2012). The importance of applying regression analysis in this study can be connected to this definition. Alternatively, it can be stated that regression analysis was applied in this study to analyze the effects of combining RAP blends with cement in the proportions of 1%, 1.5%, 2.5%, and 4% on OMC and MDD. As such, the first two regression models were dedicated for such purposes and relied on the following models to establish the related effects:

- Model 1: $\text{OMC} = \alpha + \beta_1 \text{RAP} + \beta_2 \text{Cement} + \mu$ (1).
- Model 2: $\text{MDD} = \alpha + \beta_1 \text{RAP} + \beta_2 \text{Cement} + \mu$ (2).

The symbols α represents a constant, β_1 and β_2 capture the effects of RAP and cement while μ is the error term. Furthermore, the effects of combining RAP with cement in the proportions of 1%, 1.5%, 2.5%, and 4% on CBR will be performed. The tests were monitored for seven days, and the results were regressed to ascertain their effects on CBR. Hence, the effects of combining RAP with cement were regressed for all seven days using the following regression model:

- Model 3: $\text{CBR} = \alpha + \beta_1 \text{RAP} + \beta_2 \text{Cement} + \mu$ (3).

Additionally, the effects of combining RAP with cement in the proportions of 1%, 1.5%, 2.5% and 4% on K20 were also regressed using the following regression model:

- Model 4: $\text{K20} = \alpha + \beta_1 \text{RAP} + \beta_2 \text{Cement} + \mu$ (4).

3.5.2. Optimization tests

3 mixes were prepared for optimisation analysis as follows:

1. For optimisation 1: RAP (%) = 38.199, therefore, CA%=100-38.199, Cement (%) = 2.161.
2. For optimisation 2: RAP (%) = 40.131, therefore, CA%=100-40.131, Cement (%) = 2.156.
3. For optimisation 3: RAP (%) = 28.672, therefore, CA%=100-28.672, Cement (%) = 2.446.

4. RESULT and DISCUSSION

4.1. Introduction

The results of a laboratory study of Cement stabilized RAP\CA blends and RAP\Crushed aggregate blends as base materials are presented in this research. The Modified Proctor (MDD and OMC) test, soaking CBR test, and the constant head permeability test was performed on the RAP\Crushed aggregate mixes with proportions of 100%/0%, 80%/20%, 60%/40%, 40%/60%, 25%/75%, 10%/90%, and 0%/100%. The fives samples were made using 0%, 1%, 1.5%, 2.5%, and 4% pozzolanic cement secured in plastic bags at room temperature for 24 hours and seven days. The following tests are part of the primary testing program:

- RAP and crushed aggregate physical characterization (ASTM C136-06) (ASTM D4318-05).
- Compaction testing using a modified Proctor (ASTM D1557-12 and ASTM D2216-05).
- California Bearing Ratio test according to (ASTM D1883-07).
- Constant head permeability test according to (ASTM D2434-68).

4.2. Sieve Analysis for RAP and Crushed Aggregates

Various samples were sieved, and the results RAP particle sizes between 0.075mm and 0.425mm are below the specified limits. Furthermore, RAP particles sizes of 12.5mm had a passing rate of 83%, and the passing rate exceeded the passing limit when bigger particle sizes were introduced. Thus, the tested RAP samples did not fulfill the graduation criteria for the base, as indicated in Figure 4.1. As a result, it is possible to conclude that the RAP material cannot be used as a road base material. To reuse RAP material in road

improvements, a particle size modification of this material is necessary. This material may be improved by combining it with well-graded crushed aggregate.

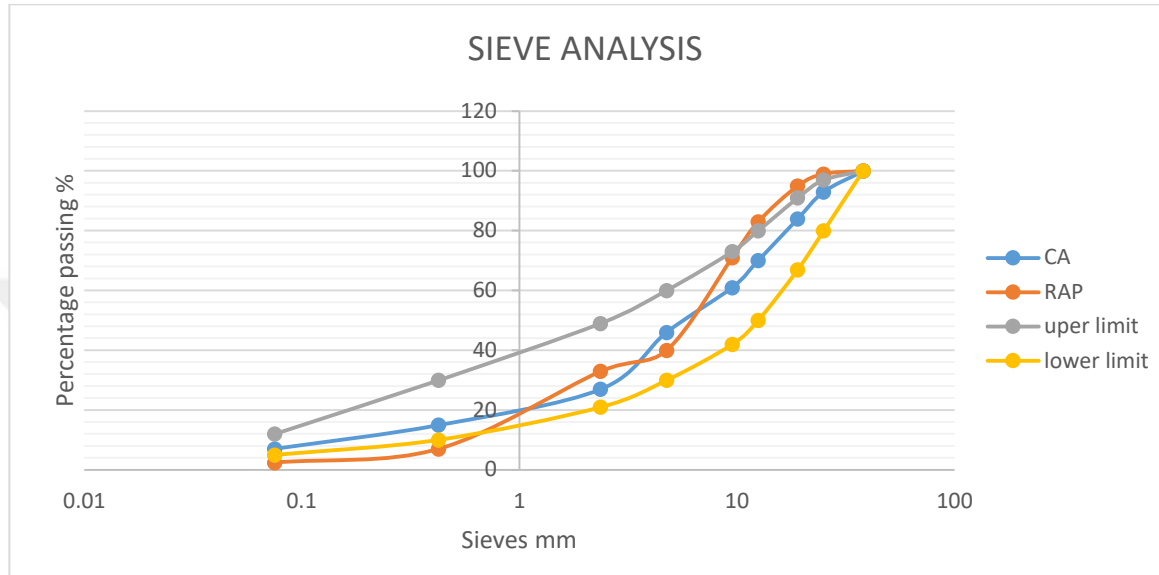


Figure 4.1. Sieve analysis for RAP and crushed aggregate

4.3. Modified Proctor Tests of RAP and CA

To assess the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) correlations, modified proctor tests were performed on blends in accordance with ASTM D1557-12 and ASTM D2216-05. The density of milled or treated RAP material is affected by the type of aggregate used in the recycled pavement and the moisture content of the stored material. Although the existing literature on RAP provides minimal data on density, the MDD of milled RAP has been reported to vary from 1.94 to 2.30 t/m³, which is somewhat lower than that of CA (Potturi, 2006). Due to the bitumen covering the RAP aggregates, which inhibits compaction, the compacted dry densities of RAP/Crushed Aggregate blends continue to decrease as the RAP percentage increases (see Figure 4.2). It is discovered that when the RAP fraction of the base course grows, the necessary OMC for maximum compaction decreases (Locander, 2009) (see Figure 4.3). Previous research verified this result, which discovered that increasing RAP content led to a decrease in

MDD and OMC values (Guthrie et al., 2007). The MDD and OMC values increased as Cement was added to the RAP material (Alireza et al., 2014). As a result, it was considered acceptable for a material with high water absorption, such as Cement, to achieve this increase, as demonstrated in Figure 4.4 and Figure 4.5.

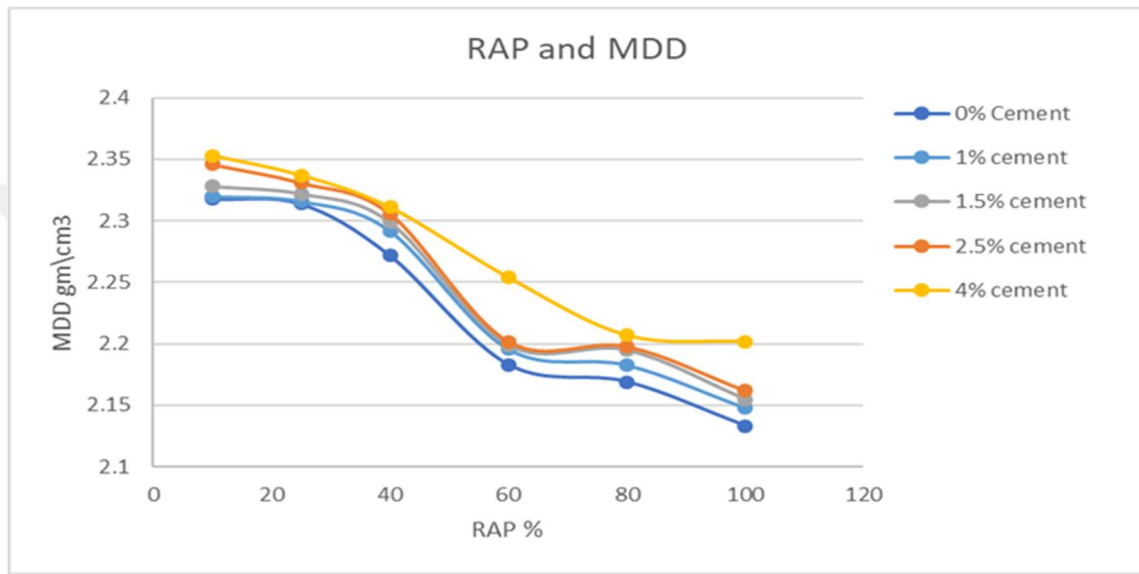


Figure 4.2. MDD with RAP\CA blends

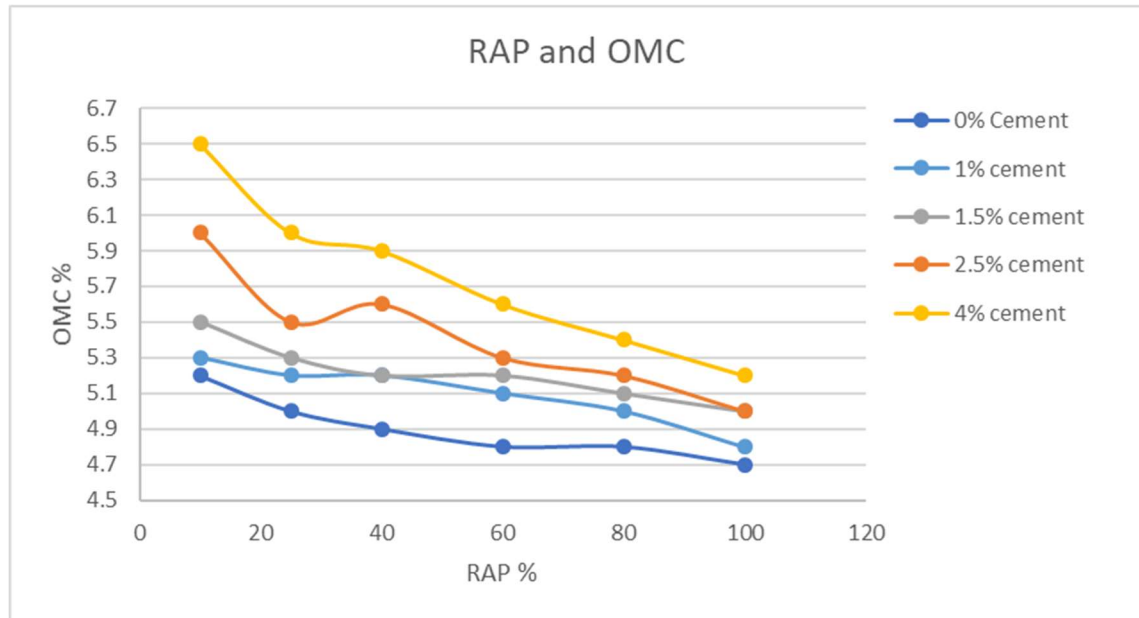


Figure 4.3. OMC with RAP\CA blends

The average OMC of a compacted RAP mixed material was lower than CA (Mokwa and Peebles, 2008). However, the OMC was shown to be more significant for RAP mixes treated with Cement because of these fines' increased acceptable content and adsorbing property. Higher OMC values were recorded when the cement content was increased from 1%, 1.5%, 2.5%, to 4%, as illustrated in Figure 4.4. This is because cement (fine particle size material) needs more moisture for hydration processes.

The tested crushed aggregate materials had a maximum dry density of 2.321 g/cm³ at the optimum moisture content of 5.5%. However, the addition of RAP materials with a maximum dry density of 2.133 g/cm³ at the optimum moisture content of 4.7% decreased the maximum dry density of crushed aggregate materials. Therefore, it also reduced the optimum moisture content, as shown in Table 4.1.

Figure 4.4 results align with Figure 4.5 results and show that higher MDD values in grams per cubic meter were recorded when the cement content was increased from 1%, 1.5%, 2.5%, to 4%. Thus, the hardness of the pavement increased following an increase in MDD. However, greater OMC and MDD values were recorded following an increase in cement content added to the RAP and CA blends (see Figure 4.4 and Figure 4.5).

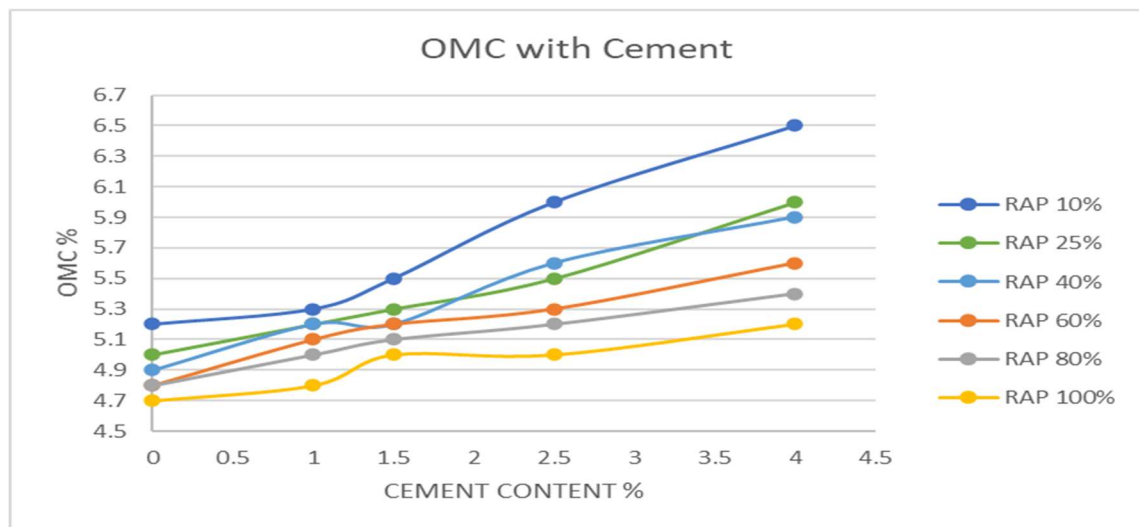


Figure 4.4. OMC with Cement content in RAP\CA blends

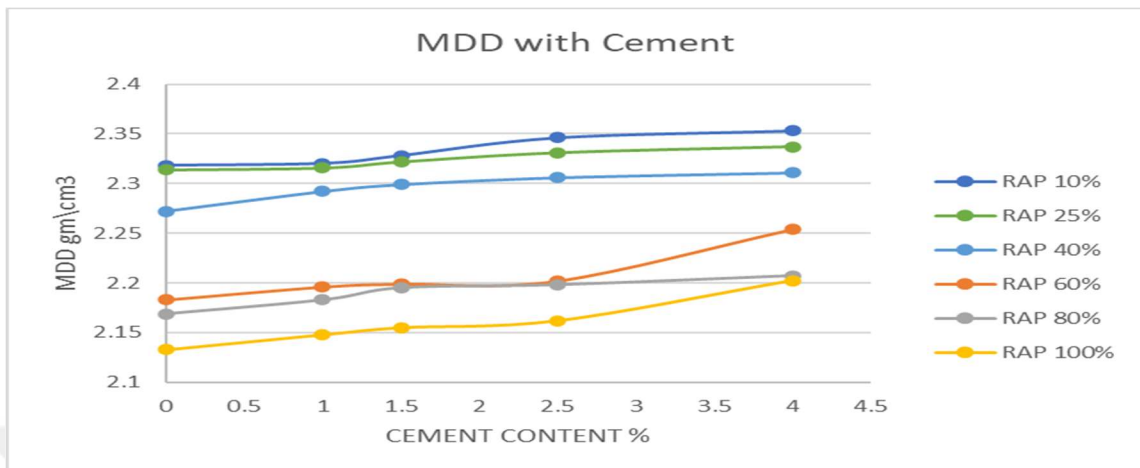


Figure 4.5. MDD with Cement content in RAP\CA blends

4.4. Bearing Capacity Ratio of RAP and CA Blends

The soaking CBR tests were performed in conformance with ASTM D1883-07. CBR is, therefore, the ratio stated as a percentage of force per unit area. The soaking CBR values of specimens containing various percentages of RAP material are shown in Figure 4.6 results. The conclusion of the CBR test of the blended materials indicates that increasing the amount of RAP material in the mix reduces the CBR values. In conclusion, the blended material containing less than 40% RAP met the standards for materials suitable for use in a road's base layer, which CBR must be greater than equal to 80%.

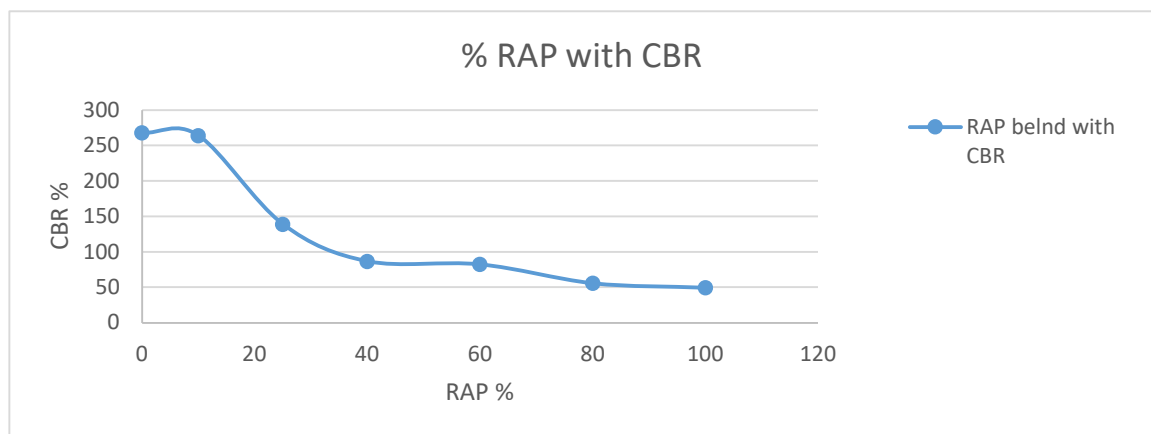


Figure 4.6. The effect of RAP\CA blend composition on the CBR

All samples studied indicated a drop in CBR values as the amount of RAP material in blends increased. When Figure 4.6 is inspected, it can be noted that the CBR value of RAP is 49.7% lesser than that of CA, which is 268%. Several writers noticed a similar pattern in CBR data (Ayan, 2011).

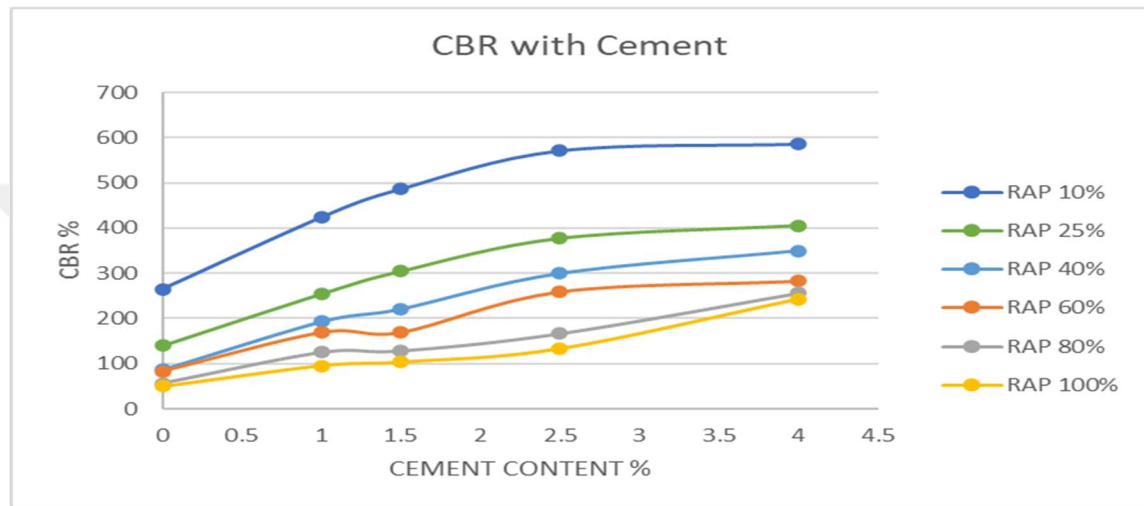


Figure 4.7. The effects of RAP\CA's cement percentage composition on the CBR

According to the results, increasing the percentage amount of Cement increases the CBR value of RAP\CA mixes, as demonstrated in Figure 4.7. As the RAP in the materials used in the test sample increases, so does the OMC, MDD, and CBR decrease.

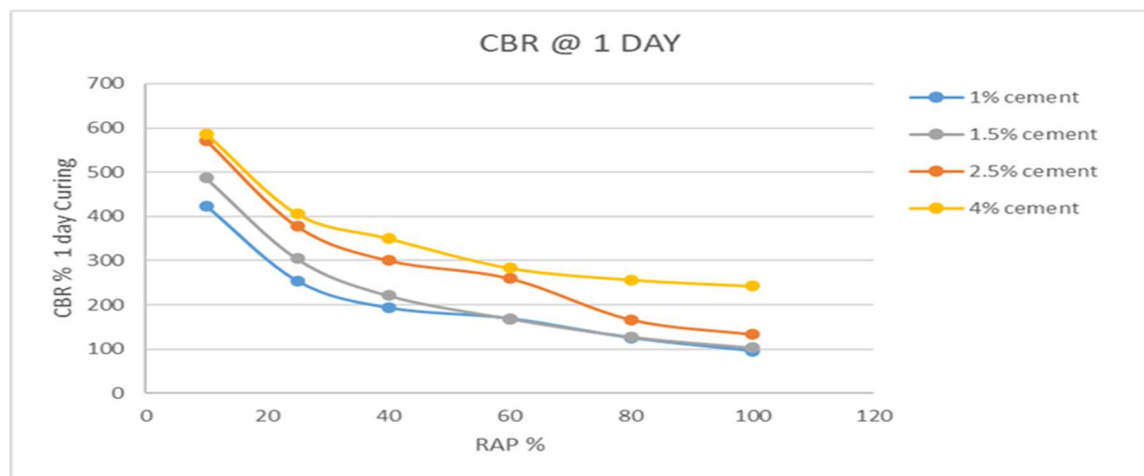


Figure 4.8. The CBR with RAP\CA blend after one day of curing cement

The bitumen-coated aggregates in the RAP strengthened significantly over time, such that RAP samples including 1.5% cement yielded CBR values exceeding 103.6% after one day of curing, as shown in Figure 4.8 and 122.3% after seven days of curing, as shown in Figure 4.9, CBR values for RAP material increased from 49.7% to 250% as the cement content increased from 0% to 4%. The bearing capacity of RAP\CA mixed material is mainly proportional to the ratio of RAP to CA. The results were obtained after one day of curing using the same amount of cement, as demonstrated in Figure 4.8. In practice, when the RAP percentage increases, the CBR value decreases (Trzebiatowski and Benson, 2005).

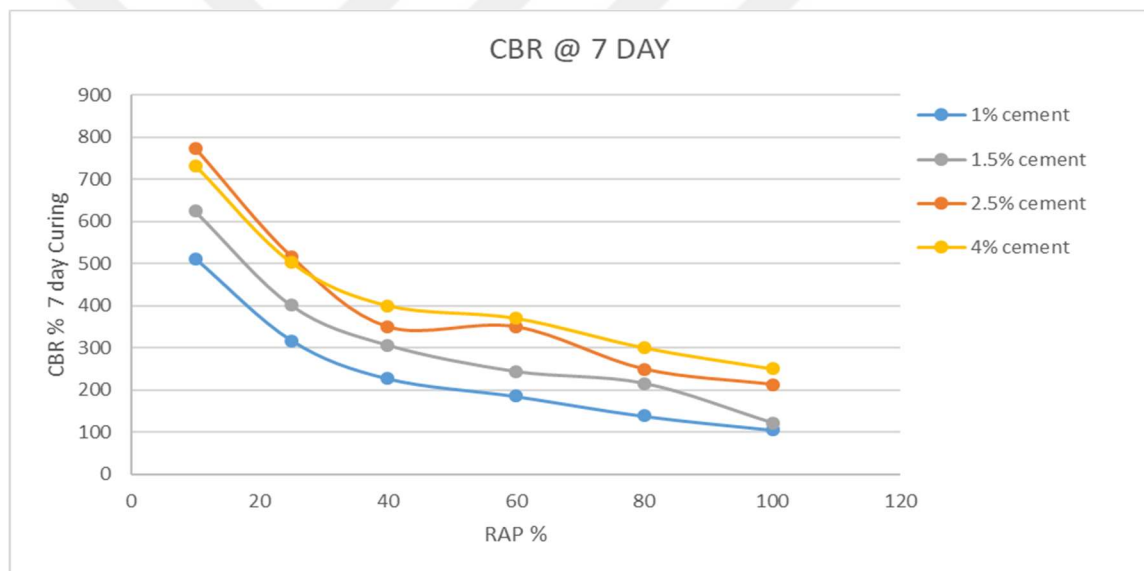


Figure 4.9. The CBR with RAP\CA blends after seven days of curing cement

4.5. Permeability Characteristics of RAP and CA Blend

Permeability is the rate at which a liquid flows through a porous material. It is considered an essential characteristic for base course materials due to its impact on pavement serviceability. As a result, evaluating the influence of RAP % on the permeability of base course materials containing RAP is critical for appropriate pavement design.

Thus, the purpose of this study is to assess the effects of RAP percentage on the permeability of unbound base materials. Crushed aggregates have a high overall permeability value because the interlocking of the asphalt-coated aggregates in RAP and the CA particles reduced the air voids, the aggregates became impermeable. As a result, the k value decreased as more excellent RAP content was added to the blend. The permeability of RAP blends declined as the proportion of RAP materials in the mix increased, as seen in Figure 4.10.

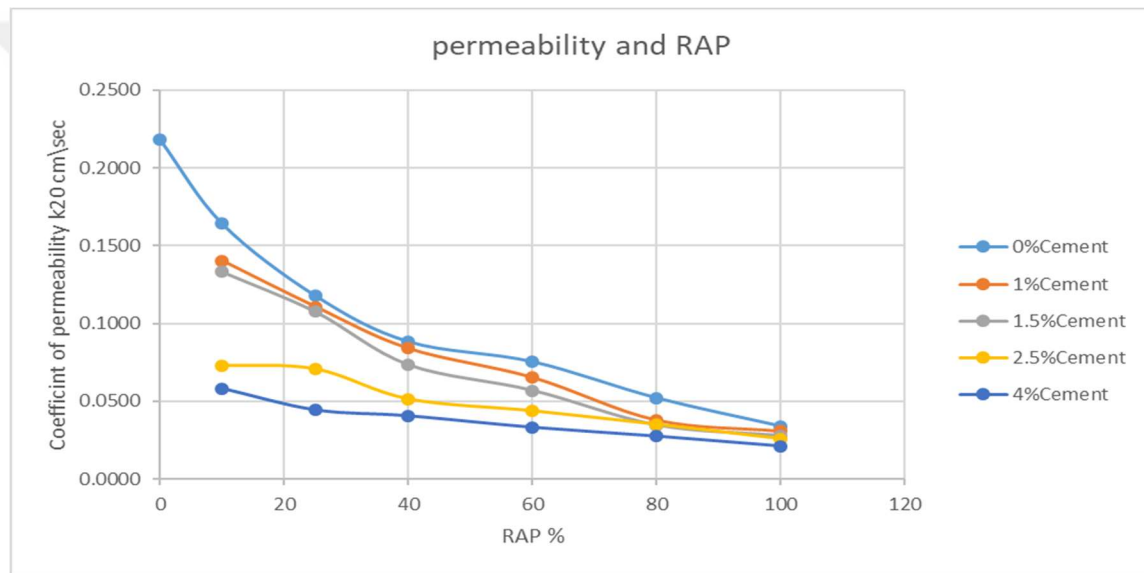


Figure 4.10. The permeability with RAP\CA blends

As demonstrated in Figure 4.11, the k value reduces as the cement percentage in the RAP\CA blend increases. However, the Permeability of cement-treated RAP\CA material decreases as the cement percentage in the blend increases. The results indicate that the addition of RAP reduces the specimen's porosity (interconnected voids). On the other hand, Low Permeability enhances the period of moisture content in the base layers, weakening the base layers' stiffness and decreasing pavement performance.

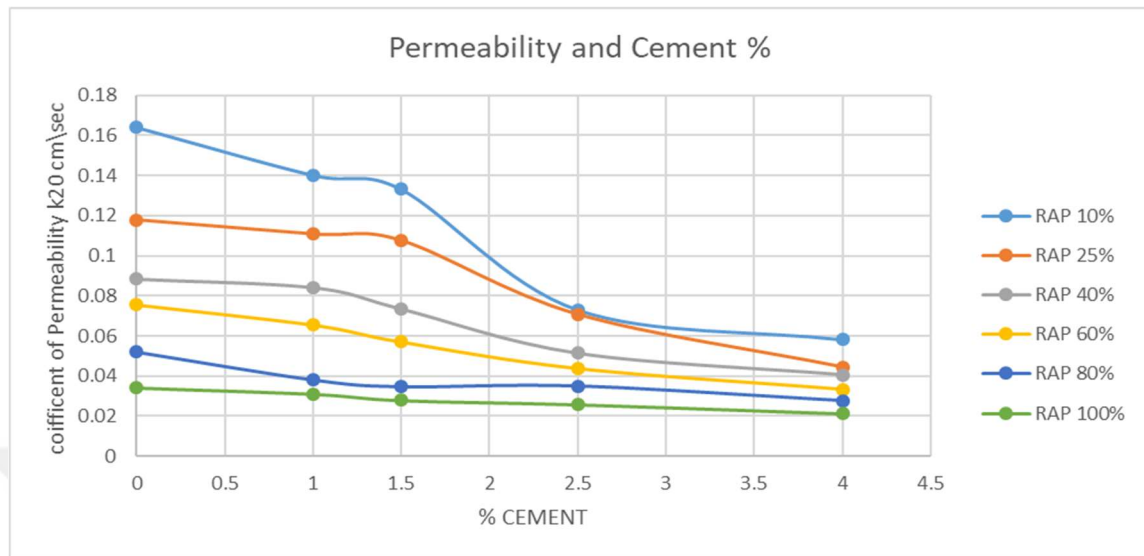


Figure 4.11. The permeability of adding cement in blend after one-day curing

The hydraulic conductivity of granular materials is affected by particle size and void ratio; hydraulic conductivity reduces as the void ratio decreases (Côté et al., 2011). Sufficient void space in the compacted specimen improves the sample's capacity to drain, increasing Permeability. Based on the void ratio study, it is inferred that the low air void content of specimens containing a high proportion of RAP is one of the causes of the decreased permeability.

Following the ASTM D2434-68 test method, the constant-head method was chosen for permeability testing based on the usual gradation used in this study. Fewer than 10% of the particles pass the 75-micro meter sieve. Therefore, the samples with differing quantities of RAP were well mixed. Samples were compacted in thin layers in to a 20 mm heighter than of permeability cylinder apparatus to above the upper manometer outlet. The distance between the bottom of the permeameter and the top manometer outlet in this investigation is 200 mm.

According to the standards for the base course, the CBR value must be up to 80%; in this study, the value of 80% was raised to 100%. Thus, if any mixture had the CBR value within 100% or more was accepted, and it is no need to use cement with the RAP\CA

blend, but for the RAP\CA blends which have the CBR value lesser than 100% value, the different ratio of pozzolanic cement was added to the RAP\CA mix. Cement was added to each one of them for the testing. The cement ratios were 1%, 1.5%, 2.5%, and 4%. All of the experiments were performed with and without the addition of cement. The test results indicate that in the test sample that was concluded on the rise of RAP in the blend, the maximum dry density decreases as the RAP percentages increase. By adding the cement, it exhibits an increase in MDD.

Furthermore, it is shown that in the test sample that was concluded on the increase of RAP in the blend, the Optimum Moisture content declines as the RAP rises, and by adding the cement, it exhibits an increase in OMC. Furthermore, the tests showed that in the test sample that was concluded on the rise of RAP ratio in the blend, the CBR decreases as the RAP increases. By adding the cement, it exhibits an increase in the CBR value.

The permeability test for crushed aggregate without cement shows that permeability reduces as RAP increases. Even with the addition of cement to the RAP and crushed aggregate combination, the permeability decreases. This is because cement is a material that requires hydration. There are a lot of cement surface area particles. This is why more water is needed to cover the particles and provide hydration, causing the voids to shrink and the permeability to decrease. All results are illustrated in Table 4.1.

The permeability results are between (1.6×10^{-3} to 2.1×10^{-4}) m/s for blended material used are coarse and medium sand that good drainage properties the consequences for soil permeability classes is permeable layer according to table 3.5.

Table 4.1. Tests of RAP\CA and/or cement blend material

RAP (%)	Crashed Agregate CA%	Cement %	Optimum Moisture Content OMC %	Maximum Dry Density MDD (gm/cm ³)	California Bearing Ratio CBR % @ 1 DAY	California Bearing Ratio CBR % @ 7 DAY	Coefficient of permeability K ₂₀ , cm/s
10	90	0	5,2	2,318	264,3	264,3	0,1640
10	90	1	5,3	2,32	423,973	510,863	0,1402
10	90	1,5	5,5	2,328	486,835	624,503	0,1331
10	90	2,5	6	2,346	571,891	774,355	0,0731
10	90	4	6,5	2,353	586,592	732,115	0,0583
25	75	0	5	2,314	139,3	139,3	0,1178
25	75	1	5,2	2,316	253,786	317,265	0,1107
25	75	1,5	5,3	2,322	304,166	400,473	0,1075
25	75	2,5	5,5	2,331	377,085	516,569	0,0707
25	75	4	6	2,337	405,482	501,844	0,0445
40	60	0	4,9	2,272	86,9	86,9	0,0883
40	60	1	5,2	2,292	193	227	0,0840
40	60	1,5	5,2	2,299	221,3	306,5	0,0734
40	60	2,5	5,6	2,306	300	350	0,0513
40	60	4	5,9	2,311	350	400	0,0406
60	40	0	4,8	2,183	82,5	82,5	0,0754
60	40	1	5,1	2,196	168,8	185	0,0654
60	40	1,5	5,2	2,199	169	244,1	0,0569
60	40	2,5	5,3	2,202	259,5	350	0,0437
60	40	4	5,6	2,254	283,1	350	0,0333
80	20	0	4,8	2,169	56	56	0,0521
80	20	1	5	2,183	124,8	138,2	0,0380
80	20	1,5	5,1	2,195	128	215,9	0,0346
80	20	2,5	5,2	2,198	166,3	249,7	0,0350
80	20	4	5,4	2,207	256,7	300	0,0276
100	0	0	4,7	2,133	49,7	49,7	0,0340
100	0	1	4,8	2,148	95,3	105,5	0,0309
100	0	1,5	5	2,155	103,6	122,3	0,0278
100	0	2,5	5	2,162	133	213,1	0,0257
100	0	4	5,2	2,202	242,5	250	0,0212

4.6. Regression Analysis Results

Regression analysis was applied in determining how changes in the combination of RAP and cement affected the OMC, MDD, CBR on days 1 and 7 and K20. The results show that adding more RAP content causes a decrease in OMC, MDD, and K20 and a decline in CBR on days 1 and 7. Additionally, adding more cement content had adverse effects on K20 and positive impacts on OMC, MDD, and CBR on days 1 and 7 (see Table 4.2).

Table 4.2. Regression analysis results

Model	Model results	R-square	Adjusted R-square
1	$OMC = 0.092 + 4.810RAP - 7.109Cement + \mu$	0.972	0.966
2	$MDD = 11.411 + 0.149RAP + 0.170Cement + \mu$	0.987	0.974
3	$CBR_{1day} = 61.065 - 1.724RAP + 23.084Cement + \mu$	0.990	0.987
4	$CBR_{7days} = 20.501 - 0.504RAP + 8.184Cement + \mu$	0.994	0.992
5	$K20 = 1.017 + 1.673RAP - 3.329Cement + \mu$	0.989	0.985

The estimated regression models were evaluated with regards to their validity using their ANOVA test results produced from the regression analysis. ANOVA tests the significance of the estimated model as to whether it has outliers. Both models had significant F-statistics values at 1% (**OMC model:** F-statistic=10.134; p-value=0.000; **MDD model:** F-statistic=16.875; p-value=0.000; **CBR_{1day} model:** F-statistic=13.446; p-value=0.000; **CBR_{7days} model:** F-statistic=18.112; p-value=0.000; **K20 model:** F-statistic=11.623; p-value=0.000). This denotes that all the models were valid and correctly specified to examine RAP when combined with crashed aggregates are introduced and treated the RAP is treated with cement (see Table 4.3).

Table 4.3. ANOVA (analysis of variance) results

Model	Model results	F-statistics	Probability values	Significance
1	OMC model	10.134	0.000	Yes
2	MDD model	16.875	0.000	Yes
3	CBR _{1day} model	13.446	0.000	Yes
4	CBR _{7days} model	18.112	0.000	Yes
5	K20 model	11.623	0.000	Yes

4.7. Optimisation Analysis

Three mixes were prepared for optimization analysis, and the results are as follows:

1. For optimization 1: RAP (%) = 38.199, therefore, CA%=100-38.199, Cement (%) = 2.161.
2. For optimization 2: RAP (%) = 40.131, therefore, CA%=100-40.131, Cement (%) = 2.156.
3. For optimization 3: RAP (%) = 28.672, therefore, CA%=100-28.672, Cement (%) = 2.446.

A graphical illustration of the optimized results is shown in Figure 4.12 and the tabulated results in Table 4.3. Desirability levels of 50.4%, 50.8%, and 50.7% were obtained for optimizations 1, 2, and 3, respectively.

Optimization 1 results depict that the OMC and CBR for day 7 were in range as they maximized RAP and minimized cement usage. The resultant effect was observed by maximizing the CBR value at day one and minimizing K20, while the CBR value at day one was kept in range.

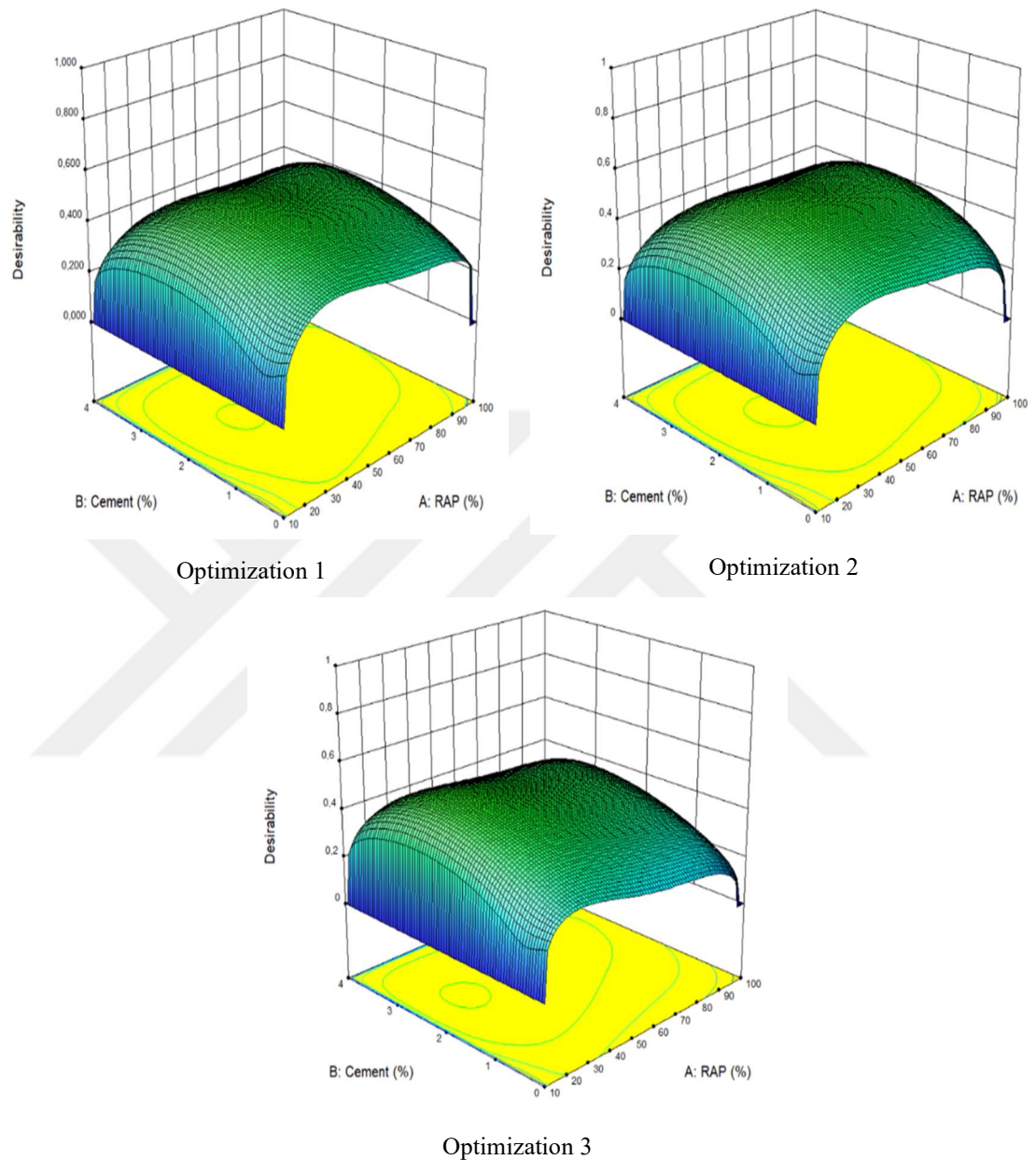


Figure 4.12. Optimization results

Regarding optimization two results, the OMC and CBR for days 1 and 7 were in range as they maximized RAP and minimized cement usage. The resultant effect was observed by maximizing the CBR value at day seven and reducing K20. Table 4.4 provides a summary of the optimized results.

Table 4.4. Optimization results

Optimization	RAP %	Cement %	OMC %	MDD g/cm ³	CBR % (Day1)	CBR % (Day7)	K20 cm/s	Desirability
1	38.199	2.161	5.390	2.295	283.524	376.135	0.063	0.504
2	40.131	2.156	5.375	2.287	273.980	364.646	0.061	0.508
3	28.672	2.446	5.561	2.329	359.220	472.843	0.064	0.507

Optimization 3 results show that the MDD was maximized, while OMC was in range as the process maximized RAP and minimized cement usage. The resultant effect was observed by maximizing the CBR value on days 1 and 7 and minimizing K20.

5. CONCLUSION and RECOMMENDATION

The main emphasis of this study was to determine the possibility of using RAP together with crash aggregate to improve the performance of the base course layer and how high-quality crushed aggregate materials and/or adding chemical stabilizing agents (cement) be utilized to strengthen RAP as a component of road base courses. Additionally, this included determining the best optimal RAP-crash aggregate and chemical stabilizing agent combinations capable of effectively enhancing the quality and performance of the base course layer with regards to their bearing and permeability capacity. As a result, six different RAP\CA combinations stabilized with 0, 1.0, 1.5, 2.5, and 4% Pozzolanic cement were tested for application in road base construction. The findings of the study support the following conclusions:

- The optimum moisture content, MDD, and CBR will increase as crushed aggregate and cement content increase.
- According to this investigation, RAP is a poor material for carrying capacity when applied independently. As a result, it should be blended with CA and/or cement.
- Pozzolanic cement can also be used to improve base course performance by increasing bearing capacity and decreasing permeability.
- After blending to meet the appropriate grading as per standards for road base materials, it was discovered that RAP materials might be successfully utilized in the base layer of road pavement.
- A 100 percent RAP might be used as a standard base course material if stabilized with Cement.
- A constant-head permeameter test was used to perform permeability measurements on samples with RAP as the base course material. According to the conclusions, the addition of RAP decreased the permeability of the base course materials.

- The crushed aggregate specimens demonstrated higher air void contents than the RAP material, suggesting that low air void contents may be one source of reduced Permeability in samples with a high RAP %.
- Effects of crushed aggregate blended with RAP, there are considerable economic and environmental benefits to lowering the number of crushed aggregate materials required in road construction related to the addition of useless RAP material.
- The CBR value decreased significantly as the RAP ratio in the mix increased. However, improved bearing capacity with cement treatment resulted in a linear increase in CBR values. As a result, it has been determined that cement is an appropriate stabilizing material for increasing the utilization of RAP material.
- The base course became more impermeable when the percentage of RAP or cement was increased.

Given the above observations, using the CA, RAP, and cement blends as a base course in parking areas, roads, and road shoulders is advisable to enhance their permeability and performance. Additionally, the obtained results demonstrate that the CA, RAP, and cement blends properties make it feasible to use them in constructing roads in villages and rural areas. Such is vital for lowering developmental, rehabilitation, and maintenance costs.

Future studies can incorporate different types of cement other than pozzolanic cement and ascertain their validity to stabilize RAP when applied in various countries like Iraq. Additionally, the study encourages the incorporation of nanomaterials for use in similar structures as there are increasingly become a significant research issue that can enhance the strength and performance of road pavement.

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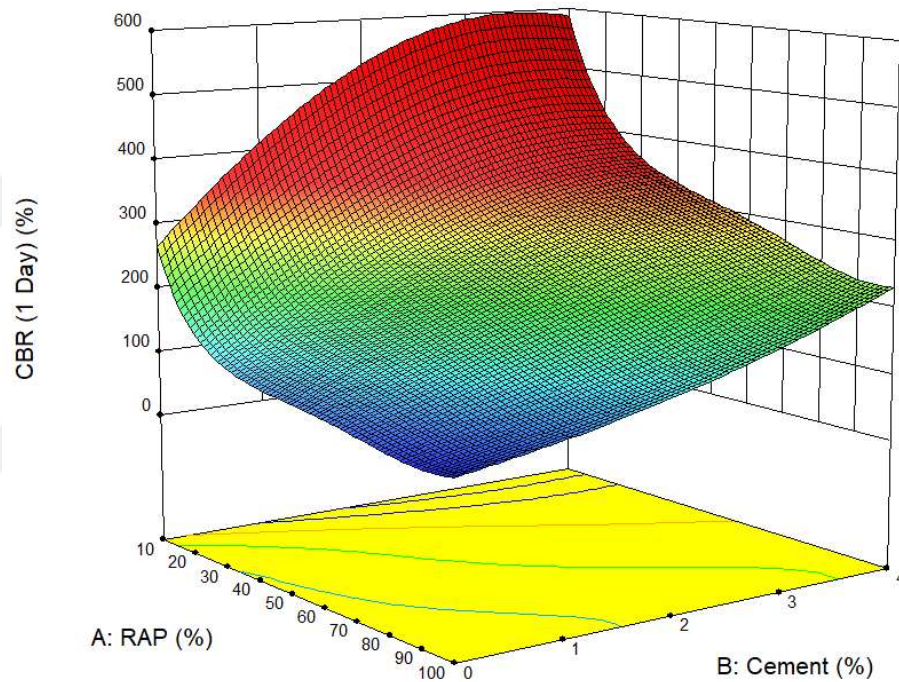
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APPENDICES

Appendix 1

Regression analysis for the missing CBR (1 Day) values

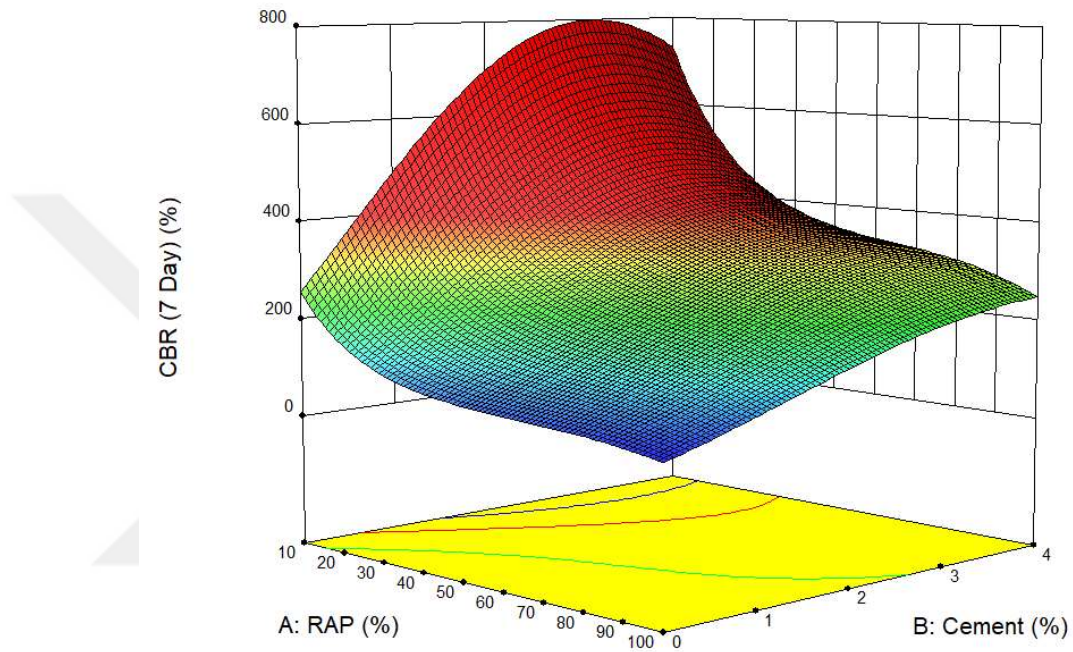


$$\begin{aligned}
 (\text{CBR (1 Day)})^{0,76} = & \\
 & +108,22551 \\
 & -4,92426 * \text{RAP} \\
 & +37,83105 * \text{Cement} \\
 & -0,31010 * \text{RAP} * \text{Cement} \\
 & +0,11878 * \text{RAP}^2 \\
 & -5,75750 * \text{Cement}^2 \\
 & +0,066334 * \text{RAP} * \text{Cement}^2 \\
 & -1,28648\text{E-}003 * \text{RAP}^3 \\
 & +5,04415\text{E-}006 * \text{RAP}^4
 \end{aligned}$$

R-Squared	0,9834
Adj R-Squared	0,9731
Pred R-Square	0,9257
Adeq Precisor	31,625

Appendix 2

Regression analysis for the missing CBR (7 Day) values

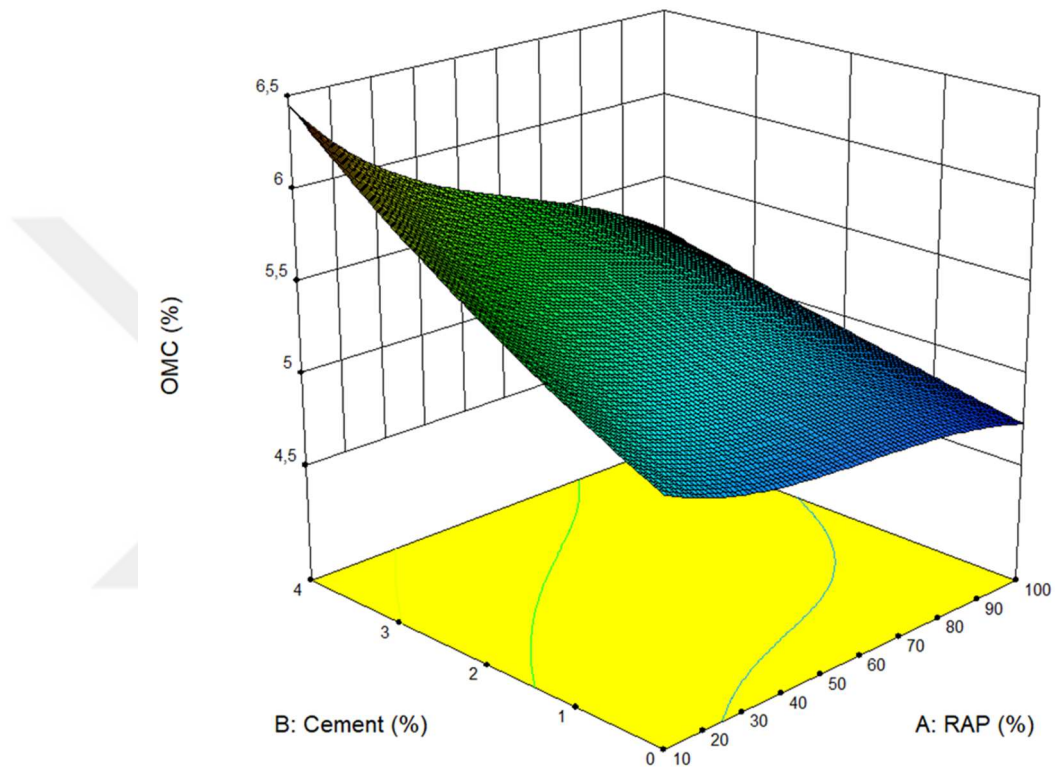


$$\begin{aligned} (\text{CBR (7 Day)})^{0,43} = & \\ & +13,36260 \\ & -0,28674 * \text{RAP} \\ & +4,65974 * \text{Cement} \\ & -0,020384 * \text{RAP} * \text{Cement} \\ & +4,04542\text{E-}003 * \text{RAP}^2 \\ & -0,77564 * \text{Cement}^2 \\ & +4,74207\text{E-}003 * \text{RAP} * \text{Cement}^2 \\ & -2,00816\text{E-}005 * \text{RAP}^3 \end{aligned}$$

R-Squared	0,9832
Adj R-Squared	0,9747
Pred R-Square	0,9452
Adeq Precisor	36,213

Appendix 3

Regression analysis for OMC

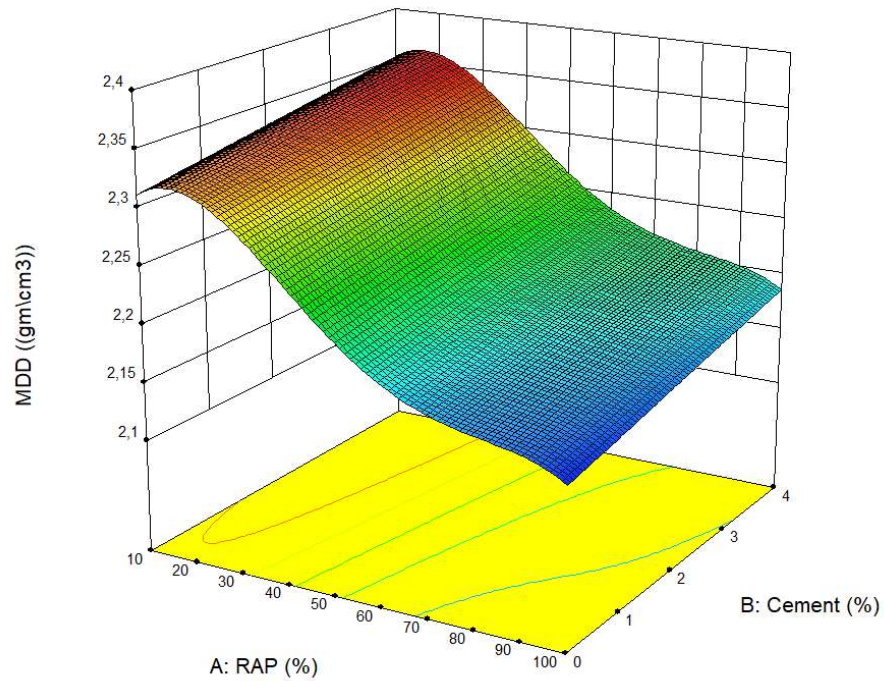


$$\begin{aligned} (OMC)^{1,43} = & \\ & +0,092339 \\ & +4,80959E-004 * RAP \\ & -7,10858E-003 * Cement \\ & +3,65510E-005 * RAP * Cement \\ & -7,35794E-006 * RAP^2 \\ & +4,15049E-008 * RAP^3 \end{aligned}$$

R-Squared	0,9722
Adj R-Squared	0,9664
Pred R-Square	0,9577
Adeq Precisor	49,850

Appendix 4

Regression analysis for MDD

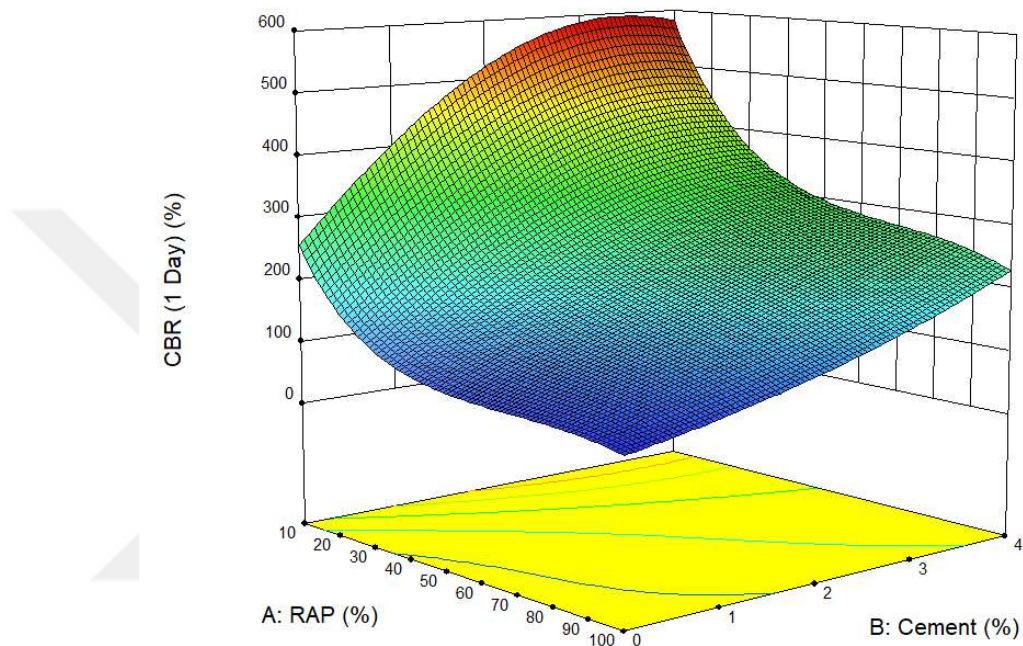


$$\begin{aligned} (MDD)^3 = & \\ & +11,41135 \\ & +0,14945 * RAP \\ & +0,16968 * Cement \\ & -6,12234E-003 * RAP^2 \\ & +7,48386E-005 * RAP^3 \\ & -3,01833E-007 * RAP^4 \end{aligned}$$

R-Squared	0,9782
Adj R-Squared	0,9736
Pred R-Square	0,9674
Adeq Precisor	41,355

Appendix 5

Regression analysis for CBR (1 Day)

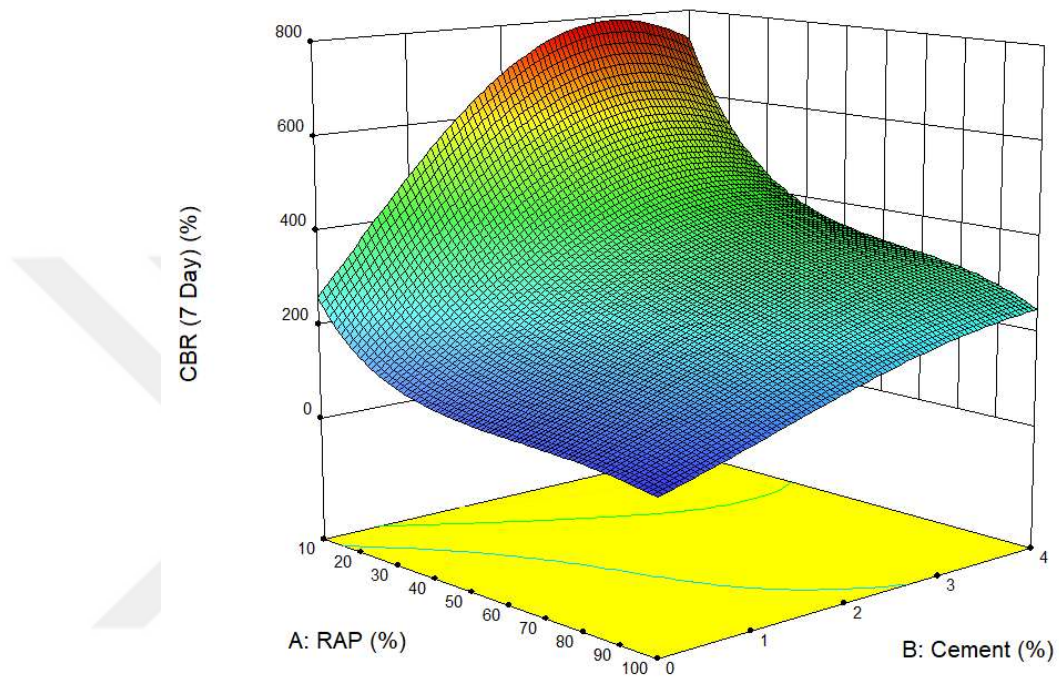


$$\begin{aligned}
 (\text{CBR (1 Day)})^{0.69} = & \\
 & +61,06471 \\
 & -1,72427 * \text{RAP} \\
 & +23,08432 * \text{Cement} \\
 & -0,17984 * \text{RAP} * \text{Cement} \\
 & +0,023746 * \text{RAP}^2 \\
 & -3,55009 * \text{Cement}^2 \\
 & +0,039662 * \text{RAP} * \text{Cement}^2 \\
 & -1,10683\text{E-}004 * \text{RAP}^3
 \end{aligned}$$

R-Squared	0,9903
Adj R-Squared	0,9872
Pred R-Square	0,9826
Adeq Precisor	61,940

Appendix 6

Regression analysis for CBR (7 DayS)

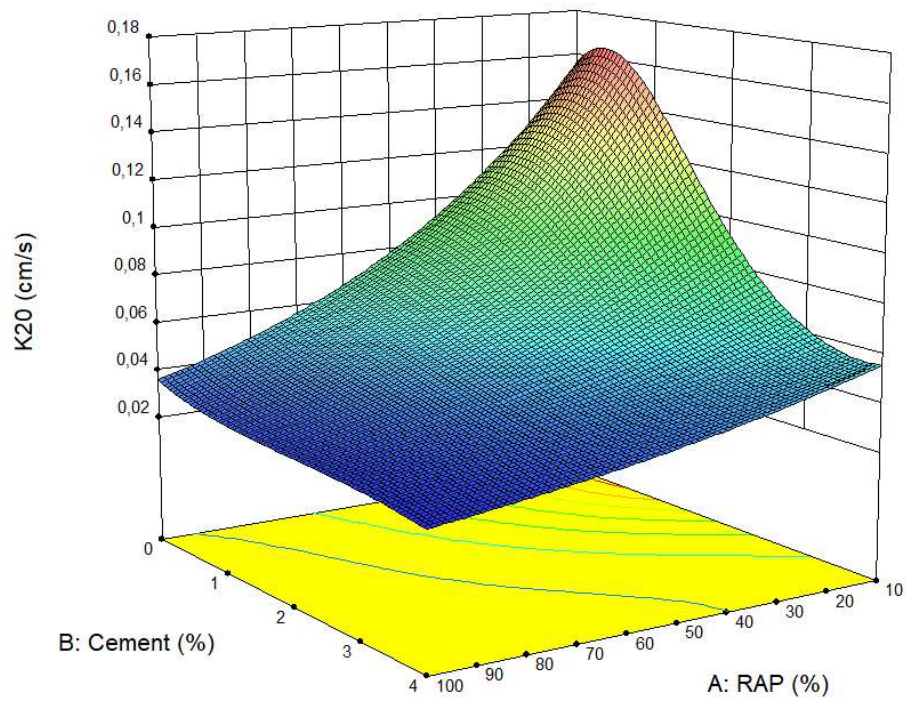


$$\begin{aligned} (\text{CBR (7 Day)})^{0.5} = & \\ & +20,50117 \\ & -0,50440 * \text{RAP} \\ & +8,18380 * \text{Cement} \\ & -0,040910 * \text{RAP} * \text{Cement} \\ & +7,22696\text{E-}003 * \text{RAP}^2 \\ & -1,35329 * \text{Cement}^2 \\ & +9,03404\text{E-}003 * \text{RAP} * \text{Cement}^2 \\ & -3,57306\text{E-}005 * \text{RAP}^3 \end{aligned}$$

R-Squared	0,9938
Adj R-Squared	0,9919
Pred R-Square	0,9890
Adeq Precisor	82,402

Appendix 7

Regression analysis for K20



$$\begin{aligned} (K20)^{0,01} = & \\ & +1,01706 \\ & +1,67294E-004 * RAP \\ & -3,32855E-003 * Cement \\ & +6,83643E-005 * RAP * Cement \\ & +4,15361E-003 * Cement^2 \\ & -5,58842E-005 * RAP * Cement^2 \\ & -6,55818E-004 * Cement^3 \\ & +8,77311E-006 * RAP * Cement^3 \end{aligned}$$

R-Squared	0,9886
Adj R-Squared	0,9849
Pred R-Square	0,9782
Adeq Precisor	55,544