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An Investigation Was Conducted into the Effect of Using Modified Waste Concrete Aggregates on the Volumetric and Mechanical Properties of Hot Asphalt Mixtures and Asphalt Quality

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Abstract

Compared to Natural Aggregates (NAs), waste concrete aggregates exhibit weaker mechanical and physical properties due to their weakly bonded, highly porous cement mortar. Therefore, their use in asphalt mixtures reduces their resistance to various types of damage. Therefore, in this study, to reduce permeability and increase the strength of bonded cement mortar, waste concrete aggregates were modified by two methods: chemical (coating their surfaces with a styrene butadiene rubber polymer) and physical (separation of cement mortar using heating), and used in asphalt mixtures. The findings showed that adding coarse aggregates from unmodified waste concrete up to 50% reduces the flow number and rutting resistance in asphalt mixtures. Also, using unmodified waste concrete aggregates as part of the coarse aggregate at 25% and 50% reduces the fatigue life of asphalt mixtures.

Keywords: Waste concrete aggregates, Styrene butadiene rubber polymer, Fatigue life, Dynamic creep.

1 | Introduction

Cantero-Durango et al. [1] conducted a study titled properties of Hot Mix Asphalt (HMA) with Multiple Recycled Concrete (RCA) contents [2]. Continuous research efforts have been developed in the literature to enhance the sustainability components of the road infrastructure industry, namely, reducing potential pollutants and increasing financial profitability [3].

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In this regard, this research aims to investigate the feasibility of producing HMA by incorporating RCA as a partial replacement for coarse Natural Aggregates (NAs). Therefore, four different HMAs were considered, namely HMA with coarse RCA contents of 15, 30, and 45% [4].

Specifically, the mechanical properties and stability of asphalt mixtures were determined [5]. On the one hand, Marshall design parameters, elastic modulus, moisture sensitivity, groove resistance, and fatigue life were considered as mechanical properties [6].

Meanwhile, considering sustainability characteristics, environmental impacts, and production costs, these were estimated using Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA), respectively [7].

As a result, the following results were obtained: 1) With the increase of coarse RCA content, the mechanical behavior of HMA gradually worsens [8].

2) This reduction in mechanical performance is acceptable up to 15% of the coarse RCA, while for higher doses, this change is abrupt; and 3) RCA only provides sustainable benefits at a replacement amount of 15%. Nasser et al. [9] conducted a study entitled "Evaluating the effects of using recycled asphalt pavement and RCA on the behavior of HMA."

In this study, the performance of HMA mixtures containing RAP and RCA was evaluated in terms of stability, flow, and Marshall volume properties to verify their suitability as a replacement for NA in flexible pavement surfaces. The HMA mixture layers of the experimental work were divided into two stages [10].

The first phase examined crushed limestone, white hard rock, and basalt aggregate materials with a maximum nominal aggregate size of 19 mm. The second phase studied the replacement of crushed limestone, by weight, with RAP and RCA at different asphalt cement contents. Coarse and fine aggregates of recycled materials were used in four 25%, 50%, 75%, and 100%, respectively.

Experimental test results showed that replacing limestone with recycled aggregate materials affects the mechanical properties, mainly the volumetric properties, of HMA. The use of RCA in HMA exceeded the 5% upper limit for air voids and increased the Optimal Asphalt Content (OAC) to 5% and 96 for mixes prepared with 50% RCA [11].

The results also showed that adding RAP aggregates to limestone in HMA improved Marshall stability, with the highest value of 29.32 kN recorded for asphalt mixtures prepared with 75% RAP at 3% asphalt content. The combination of RAP and RCA aggregates showed that with increasing RCA ratio in the mixture, lower load capacity and higher OAC were observed compared to other asphalt mixtures [12].

2 | Hot Asphalt Pavement

One of the factors that plays an important role in transportation infrastructure throughout the world and ultimately in the global economy is asphalt pavement, which is used both in the construction and maintenance of highways and main roads, asphalt, and for rural roads and urban streets, airport runways and taxiways, Private roads, parking lots, bridge decks, sidewalks, cycling and sports paths, and play areas. The two continents of Europe and North America are among the most extensive in the world for paved roads and highways.

Based on estimates from Europe, more than 90% of the 5.2 million kilometers of roads and highways are paved. In the United States, more than 92% of the more than 4 million kilometers of roads and highways are paved with asphalt. Also, about 85% of airport runways and 85% of parking areas in the United States are paved with asphalt.

Canada also has approximately 415,000 kilometers of paved roads, with about 90% of roads paved.

There are approximately 344,000 kilometers of paved roads in Central and South America, about 64,000 kilometers in Australia and New Zealand, about 1.5 million kilometers in China, and 2.5 million kilometers in the rest of Asia.

In Europe, the total annual asphalt production is about 435 million metric tons, and in the United States, about 410 million metric tons (European Standard, 2011). These pavements are generally paved with asphalt mixtures. Asphalt mixtures typically consist of about 95% NA mixed with 5% asphalt, and the asphalt functions as a bituminous binder that binds the NAs into a cohesive composition.

The aggregates used in asphalt mixtures are naturally formed from crushed rock, sand, or minerals. To construct and maintain asphalt pavements, natural resources such as asphalt and NAs must be continuously supplied [10]. The pavement industry consumes approximately 1.36 trillion metric tons of asphalt annually.

3 | Use of Recycled Pavement Materials as Aggregate Materials

Given that recycling is well known and important, a large volume of waste is still produced. Among the appropriate and eco-friendly solutions that stand out is waste recycling for projects such as road construction and infrastructure. The most common recycled materials examined by many Departments of Transportation (DOT'S) are crushed stone, asphalt, rubber glass, and coal fly ash; therefore, recycling construction waste and using it in the construction industry leads to a reduction in the amount of waste sent to landfills and, on the other hand, increases the life of natural resources by not using existing resources [13].

In the United States, according to surveys, recycled materials are about 352 million tons to 859 million tons per year, and it has been determined that of the 41 million tons of waste produced, 33 million tons (approximately 80) are effectively used in pavement and other geotechnical constructions. Recycling existing pavement materials for rehabilitation is an old method that has been considered since 1975 [14].

4 | Asphalt Chip Materials

Over the past few years, asphalt chip materials have been touted as a sustainable and cost-effective alternative to NAs in pavement construction. Asphalt chip materials can be used as base or aggregate subbase materials in various pavements, including paved and unpaved roads, bicycle paths, gravel surface repairs, shoulders, residential roads, embankments, and pipe beds. In the United States, the highway industry produces over 100 million tons of asphalt chip material annually through the improvement and rehabilitation of existing highways [15].

5 | Density and Moisture Percentage Test

One concern with using asphalt chip materials as base course is the lack of a test method to assess in-situ compaction and moisture content of the compacted base course. Generally, the nuclear densitometer test is used by state DOT to measure the density and moisture content of compacted base course materials. However, adding asphalt chip material to the base course significantly impacts the performance of this device.

6 | Concrete Aggregates

When we talk about concrete recycling, we mean breaking, removing, crushing, and processing hardened concrete to produce RCA (crushed concrete).

Recycled concrete is a type of aggregate that is suitable as a substitute for virgin aggregate in various construction projects. *Figs. (1)* and *(2)* show images related to recycled concrete.

Fig. 1. Off-site concrete pavement recycling operation.

Fig. 2. In-situ recycling of mobile concrete pavement.

Concrete pavements are recyclable and are generally considered very suitable sources for the production of aggregates because they consist of materials that already meet the necessary quality specifications [16].

Reclaimed Concrete Materials (RCM) are sometimes referred to as Recycled Concrete Pavement (RCP) or crushed pavement. These high-quality aggregate materials typically consist of mineral aggregates bound together by a hardened cement paste. Aggregates make up approximately 60-75% of the total volume of concrete. Crushed concrete materials are produced from the demolition of a variety of Portland cement concrete elements, such as roads, runways, and structures, during road reconstruction, utility excavations, or demolition operations.

In many urban areas, aggregates are obtained from existing Portland cement concretes, pavement sections, and road sections, which may or may not be stabilized by adding a small percentage of admixtures.

Recycled concrete is generally transported to a central facility for storage and processing, or, for large reconstruction projects, processed on-site using a mobile plant. In central processing facilities, operations include crushing, screening, and the recovery of rebar and reinforcing mesh.

Existing crushing systems with magnetic separators can remove reinforced steel without much difficulty. The use of aggregates as an alternative in pavement construction is well-established and includes applications in reinforced base projects, engineered excavation aggregates, and Portland cement concrete pavements.

When using crushed concrete as aggregate, as much foreign debris and reinforcing steel as possible should be removed during processing. Most processing plants have primary and secondary crushers.

7 | Dynamic Creep Test

The creep curves of the control and modified samples at 50°C are shown in *Fig. 4*. Since the gradient of the creep curve in the second region is almost constant, if a line is fitted to the curve in this region, it is observed that the highest and lowest slopes belong to the sample containing 50% coarse aggregates of unmodified waste concrete and the control sample, respectively; Therefore, it can be concluded that samples containing coarse aggregates of unmodified waste concrete degrade more rapidly.

In addition, the results show that the use of coarse-grained waste concrete aggregates modified by both physical and chemical methods, because they are of higher quality than unmodified waste concrete aggregates, reduces the aforementioned slope and increases the resistance of asphalt mixtures containing them to rutting.

The results also show that chemical modification of waste concrete aggregates is more effective at reducing the rutting potential of samples containing them than physical modification.

The results also show that chemical modification of waste concrete aggregates is more effective than physical modification in reducing the rutting potential of samples containing them.

8 | Fatigue Testing by Indirect Tensile Method

In this study, the fatigue life of asphalt samples was determined using the indirect tensile method, and the results are shown in *Fig. 3*. Regression lines were fitted to the samples at each stress level. The results show a strong linear relationship between the logarithm of vertical stress and the logarithm of fatigue life. Also, the fatigue equation, the values of 1 and 2, and the correlation coefficients for each mixture are given in *Table 1*.

The results show that the use of unmodified waste concrete aggregates as part of the coarse aggregate at 25% and 50% reduces the fatigue life of asphalt mixtures, and the rate of reduction increases with increasing amount. Because waste concrete aggregates, despite having better adhesion to bitumen, which can help improve fatigue life, severely reduce the load capacity of asphalt specimens due to the highly porous, weak cement mortar on their surfaces. The results also demonstrate that coating RCAs with a Styrene-Butadiene Rubber (SBR) polymer, which penetrates their internal voids and enhances bonding, improves their physical and mechanical properties.

As a result, asphalt samples containing chemically modified waste concrete aggregates exhibit longer fatigue life and are closer to control mixtures than those containing unmodified waste concrete aggregates.

Also, physical modification of waste concrete aggregates by separating loose cement mortar from their surfaces through heating, similar to chemical modification, has improved the fatigue performance of asphalt samples containing them, but its effectiveness has been less than that of chemical modification.

In chemical modification, in addition to stabilizing the cement mortar with a SBR polymer, the adhesive quality at the bitumen-aggregate contact surface is improved.

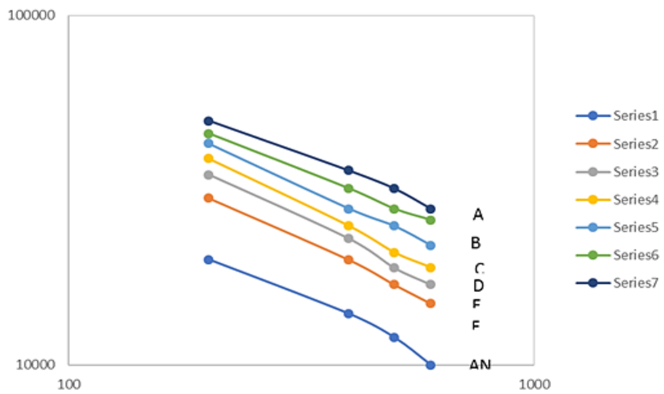

Fig. 3. Fatigue life versus stress levels for base and modified asphalt mixtures.

Table 1. Fatigue relationship presented for various asphalt mixtures.

K_2	K_1	Fatigue Equation		Mixed Type
-0.742	8×10^6	$N_f = 8\times10^6\sigma^{-0.742}$		Control
-0.896	9×10^6	$N_f = 9\times10^6\sigma^{-0.896}$	Unmodified	Contains 25% waste concrete aggregate
-0.879	1×10^7	$N_f = 1\times10^7\sigma^{-0.879}$	Modified by SBR	
-0.653	1×10^7	$N_f = 1\times10^7\sigma^{-0.653}$	Modified by heating	
-1.108	1×10^7	$N_f = 1\times10^7\sigma^{-1.108}$	Unmodified	Contains 25% waste concrete aggregate
-1.017	2×10^7	$N_f = 2\times10^7\sigma^{-1.017}$	Modified by SBR	
-1.237	4×10^7	$N_f = 4\times10^7\sigma^{-1.237}$	Modified by heating	

9 | Indirect Tensile Strength Test

The indirect tensile strength ratio index for identical asphalt mixtures under wet-to-dry conditions is among the most common indices for assessing the moisture sensitivity of an asphalt mixture before application. It can predict its performance at the design stage.

Fig. 4. Image of indirect tensile strength test.

10 | Conclusion

In this study, the feasibility of using coarse aggregates from unmodified and modified waste concrete, obtained via two physical and chemical methods, as part of asphalt mixtures was evaluated. Therefore, fatigue tests using dynamic indirect tensile creep and indirect tensile strength were conducted to determine fatigue life, rutting potential, and moisture sensitivity, respectively. Based on tests conducted on various asphalt materials and mixtures, the following results can be presented.

The results of various tests on aggregates showed that unmodified waste concrete aggregates exhibit undesirable mechanical and physical properties compared to NAs, due to the presence of highly porous, weak cement mortar on their surfaces. However, modifying them by both physical and chemical methods not only reduces their absorbency but also improves their mechanical properties.

The use of unmodified waste concrete aggregates in asphalt mixtures increases the optimal bitumen content. It reduces the effective bitumen content due to the high porosity of the bonded cement mortar. Also, in mixtures containing concrete aggregates and chemically modified waste, the optimal bitumen content is reduced because the SBR polymer acts as an insulator, reducing permeability.

The use of waste concrete aggregates in all quantities reduces the bearing capacity and fatigue life of asphalt mixtures, and both physical and chemical methods can improve their performance. The results also showed that the asphalt mixture containing 50% waste concrete aggregates has the lowest fatigue life.

Flow number values showed that the use of unmodified and modified waste concrete aggregates in all quantities reduces this index and increases the rutting potential in asphalt mixtures. Aggregate characteristics are among the most influential parameters affecting the performance of asphalt mixtures at high temperatures and the control of rutting damage.

The tensile strength of all asphalt samples decreases in wet conditions, primarily due to the negative effect on bitumen-aggregate adhesion, but in mixtures containing unmodified waste concrete aggregates, this decrease is more pronounced due to their high permeability. Results from various experiments showed that the optimal amount of waste concrete aggregate as coarse aggregate in asphalt mixtures is 25%.

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