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Laboratory evaluation of treated recycled concrete aggregate in asphalt mixtures

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Abstract

Recycled Concrete Aggregate (RCA) is considered to be a potential substitute for natural aggregates in asphalt mixtures. Despite some contradictory results achieved by researchers, it is believed that RCA treatment can improve quality of recycled asphalt mixes considerably. In this research, a two-stage treatment was applied on coarse RCA materials in order to improve their properties. The treatment was consisted of first soaking RCAs in Hydrochloric Acid (HCl); second impregnating the treated RCAs into Calcium Metasilicate (CM). The pores of RCAs were filled with CM particles. Substituting virgin aggregates with different amounts of coarse RCA materials into HMA resulted in increased tensile properties of mixes as tested in indirect tensile fatigue test (ITFT). The treatments resulted in reduced moisture sensitivity of mixes. The improvements were mostly attributed to the reduced water absorption of RCA materials. Moreover, morphological characteristics of the treated coarse RCA materials were determined using Scanning Electron Microscopy (SEM) photography.

Keywords: Recycled Concrete Aggregate (RCA); Stripping susceptibility; Calcium Metasilicate (CM); Indirect tensile fatigue test.

1. Introduction

Over the past decades, the growing amounts of Construction and Demolition Waste materials (CDW) have been a great concern for the environmental protection agencies [1]. Unlike the proper actions of recycling these materials and also re-using in different applications, the general trend is to use virgin mineral aggregates for constructing roads and other civil engineering projects. This trend will certainly have adverse effects on the environment [2]. However, lack of adequate landfill areas for damping CDW materials, and the detrimental environmental issues have conducted highway agencies to perform research works so that to find alternative solutions for recycling CDW materials [3]. In fact, road construction projects, that require huge amounts of aggregates are proper sites for using these recycled materials [4]. Production of mineral aggregates in quarries, not only have negative impacts on the environment, but it results in emission of large amounts of CO_2 gases during the processing phases [5].

Therefore, the application of Recycled Aggregates (RA) as a replacement of Virgin Aggregates (VA) in HMA mixes has beenconsidered among appropriate approaches for using recycling certain materials from CDW materials. Many researchers tried to use materials such as CDW, crumb rubber, RAP and crushed brick particles in asphalt mixes [6,7]. Composition of CDW materials is related to several parameters, including, type of structure, method of construction and types and properties of the source aggregates.

Due to desirable performance in providing easy driving, optimum stability, suitable resistance and insulation against water, asphalt concrete has most utilization in pavement construction [8]. Almost 75% by volume of the HMA consists of natural aggregates [9]. Hence, incorporation of RCA as substitution to natural aggregates (NA), not only can save natural resources but it can keep the environment safe by reducing the rate of deposit to landfills [10]. Researchers conducted several research works on the application of RCA in HMA mixes. Despite the discrepancy reported by various researchers on quality of HMA mixes containing RCAs, generally these have poor stripping resistance properties [11-13]. The quality of RCA in general is not better than natural aggregates, mainly because it contains two additional components: adhered mortar and an Interfacial Transition Zone (ITZ) between the natural aggregate and the cement mortar which is more porous than NA [14]. Fig. 1 shows the image of the RCA and its components. Therefore, RCA compared with NA, has

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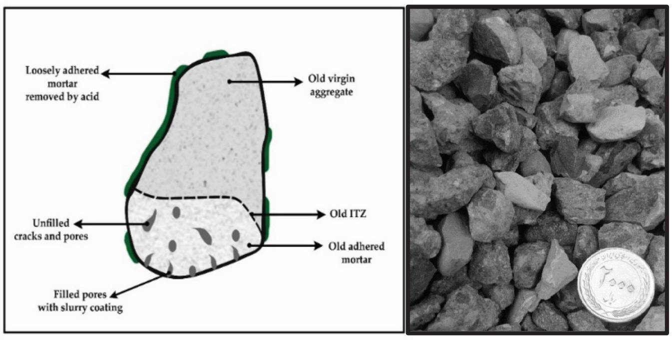

Fig. 1. RCA and components.

higher porosities and greater water absorption and lower strength. The greater water absorption of RCA results in absorbing more bitumen binder during mixing and laying processes. Greater bitumen absorption of the adhered mortar will result in mixtures with greater stripping susceptibility in HMA pavements [6]. In order toenhance quality of RCA, several treatment methods have been proposed [14]. Removing adhered mortar can be carried out using several methods, including mechanical grinding, hot grinding, water washing or pre-soaking in acid. On the other hand, there are some methods that result in strengthening the adhered mortals. Among these, the application of Nano-pozzolanic solutions for strengthen the adhered mortar are a widely used method [15]. Some treatment materials can form a water-repellent coating on the surface of RCA in order to reduce bitumen absorption rate [16]. Pozzolanic materials can fill the pores of adhered cement mortal and also react with calcium hydroxide to strengthen RCA by forming C-S-H gel [17]. RCA can be immersed in a pozzolanic slurry material or sprayed with pozzolanic solutions in order to coat the RCA surfaces. A thin pozzolanic layer that covers surfaces of the RCA particles is responsible for the reduction in water absorption rate of RCA and improving the quality of them [18]. Shayan and Xu (2003) impregnated RCA in a lime and silica fume solution. They found that silica fume could improve properties of RCA [19]. The efficiency of silica fume is because of its high surface area and activity of its particles [20]. Ismail and Ramli (2014) impregnated RCA in calcium metasilicate (CM) solution to coat RCA surface with CM particles. They concluded that the treatment enhance properties of coarse RCA significantly [21]. In general, filling the weak areas and developing stronger ITZs on RCA are the main goals in these methods.

In Tehran City, on average 19% of CDW materials, is composed of demolished concretes from building structures [22]. The compositions of typical municipal CDW of Tehran are reported in Table 1.

Therefore, one of the main parts of CDW materials is the waste concrete. This research is aimed to evaluate the usage of Recycled Concrete Aggregate (RCA) as a replacement with natural aggregates in HMA mixes. Incorporation of RCA in concrete pavements and concrete structures has already been investigated by several researchers [23-25]. The main objective of this research is to investigate the influence of different amounts of coarse RCA on properties of HMA mixes. Various proportions of RCA, namely 0%, 25% and 50%, were used for preparing asphalt mixtures. Treatment of RCA, applying different approaches were among the goals of this research. To achieve this goal, a treatment technique, consisting of pre-soaking RCA into acid and nano-pozzolanic slurry was carried out to enhance RCA characteristics, especially its excessive water absorption. Treated and untreated RCA asphalt mixtures were tested by controlling the same characteristics that were previously assessed for mixes containing natural aggregates.

Table 1
Typical composition of municipal CDW materials in Tehran.

Material	Amount (%)
Concrete	19
Broken bricks	18
sand and cement mixes	30
Soil	11
Gypsum	4.2
Asphalt materials	1.3
Stone	3
Ceramic tile	4.8
Mosaic	5
Metals	0.7
Wood	0.51
Glass	1
Cardboard and paper	1
Sack	0.5
Total	100

2. Materials and Testing

2.1 Aggregates

Two aggregates were used in this research: a normal mineral aggregate, consisting of 100% crushed particles and a recycled concrete aggregate (RCA) from construction and demolition waste (CDW) materials that were deposited at a landfill site in Tehran. From previous research works, it has been known that coarse recycled aggregates have a lower portion of adhered mortar materials, compared with fine recycled aggregates [6]. Accordingly, it is expected that the coarse recycled aggregates possess a better quality. Thus, its usage is likely to be more successful than the fine recycled aggregates. Hence, the present investigation primarily was focused on substituting mineral aggregates with coarse RCA fraction. In this context, RCA is defined as fraction of material that is retained between sieves corresponding with 4.75 and 19 mm sizes. Three portions, namely 0, 25, and 50% were used to prepare asphalt mixtures. The gradation of the virgin aggregates and various percentages of RCA were selected, as shown in Table 2. This is within the aggregate grading limits of Type IV grading of AASHTO Standard [26].

2.2 Asphalt binder

The asphalt binder was a 60/70-pen from Isfahan Refinery. Conventional laboratory tests were carried out in order to determine its physical properties. The results are summarized in Table 3.

2.3 Treatment of RCA

The coarse RCAs were washed thoroughly, so that all the noticeable impurities such as wood particles and soils were removed. Then, the coarse RCAs were dried at ambient temperature for 24 hours before conducting different types of treatments and tests.

Table 2
Grading limits of the aggregates.

Sieve size(mm)	19	12.5	4.75	2.36	0.3	0.075
Lower-upper limits	100	90–100	77–74	28–58	5–21	2–10
Passing (100%)	100	95	75	43	13	6

Table 3
Conventional bitumen testing results of the binder.

Test	Specification	Result
Flash point (°C)	ASTM D92	261
Softening point (°C)	ASTM D36	51
Loss on heating (%)	ASTM D1754	0.75
Specific gravity (°C; g/cm^3)	ASTM D70	1.022
Ductility (25°C; cm)	ASTM D113	110
Penetration (at 25°C; 0.1 mm)	ASTM D5	63

2.3.1 First surface treatment (Acid)

Acid pre-soaking treatment method was conducted to treat coarse RCA particles. The procedure begins with soaking RCA for 24h in an acidic environment at ambient temperature. Then the particles were washed with distilled water to dilute and remove the acidic solvents. The acidic solution was hydrochloric acid (HCl) with concentration of 0.1 moles. This concentration can provide a suitable acidic environment for the aggregate particles to remove the old cement mortar covering them, while it will not reduce the aggregate quality [27].

2.3.2 Second surface treatment (Calcium Metasilicate slurry)

Calcium Metasilicate (named Wollastonite) is widely used in production of ceramics, brake pad, insulation, and other construction materials. This is basically a white powder with particle sizes similar to that of cement. The specific gravity of CMs were 2.86 g/cm^3. Chemical composition of Wollastonite were reported in Table 4. The major mineral phases of the Calcium Metasilicate include quartz (SiO_2) and calcite ($CaCO_3$) [21]. Therefore, Calcium Metasilicate solution with 5% concentration was made to soak RCA for 24 h.

3. Testing

3.1 Aggregate characteristic tests

The properties of recycled and natural aggregates, in terms of water absorption (WA), density, Los Angeles Abrasion (LAA) and Aggregate Impact Value (AIV) were experimentally evaluated. In order to morphological assessment of treated aggregates Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analyzer (EDAX) analyses were conducted.

Table 4
Chemical composition of calcium metasilicate (Wollastonite).

Component	Amount (%)
SiO_2	48
Al_2O_3	0.9
Fe_2O_3	0.3
CaO	46.3
MgO	1.4
Others	3.1

3.2 Marshall Mix design

Asphalt mixtures were prepared and were compacted applying 75 blows of Marshall Hammer on each sides of the cylindrical specimens using the Standard Marshall Mix design procedure. Separate cylindrical samples were fabricated for performing Marshall, Indirect Tensile Strength (ITS) and fatigue tests (three samples for each test). After samples preparing and before compacting, samples were maintained for two hours at assigned compaction temperature to simulate short-term aging and ensure that the asphalt binder absorption by aggregate particles has occurred. The mixing temperature was 163°C, whereas the compaction temperature was 150°C. For RCA mixtures, three proportions of 0, 25 and 50% were added as partial substitution of coarse NA.

3.3 Indirect tensile fatigue (ITF) test

Proper assessment of the fatigue behavior of asphalt mixture is important to design an excellent asphalt pavement to prevent premature fatigue cracking. Researches indicated that the fatigue cracking is created due to the concentration of tensile strains at the bottom of the asphalt pavement layer caused by repetitive traffic loading [28]. The indirect tensile fatigue test characterizes fatigue behavior of mixtures. Fatigue tests were carried out at both controlled strain and controlled stress modes. In controlled strain mode, strain was maintained by reducing the stress on the sample. In controlled stress mode, this was held constantly to increase the strain within the sample [7,29]. Relationship between the tensile strain and the number of cycles to failure for each materials was established. Fig. 2 shows a sample of load-deformation curve that was achieved in this research. For each specimens, horizontal deformations were recorded and the curves were drawn automatically. In Fig. 2, N1 and N2 are the two different definitions of fatigue life, as defined in European Standard: EN 12697, Part 24.

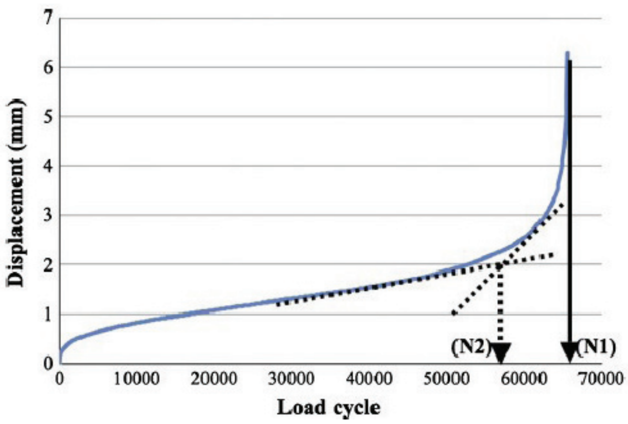

Fig. 2. A sample of load-deformation curve with fatigue life definitions in ITFT method.

N1 is the number of load cycles for complete sample failure. N2 is the loading cycle corresponding with fatigue initiation [30].

A wide variety of methods have been developed to evaluate fatigue behavior of asphalt mixtures; these include dissipated energy, Wohler and fracture mechanics methods. It has been considered that there is a logarithmic linear relationship between tensile strain and number of loading cycles required to failure. The regression analysis was used to predict fatigue life by Wohler's fatigue prediction equation, as shown in Eq. (1) below [7,29,31].

$$N_f = a\left[\frac{1}{\varepsilon_t}\right]^b \quad (1)$$

where ε_t is the applied strain, N_f is the number of cycles to failure. Power b is assumed to be 4. Universal testing machine (UTM-14) apparatus was used to determine fatigue life of the specimens (Fig. 3). With this constant stress and amplitude was applied in the direction of the specimen's asymmetric axis. The UTM chamber had a reference specimen on that two thermocouple were mounted. These measured the skin and the core temperatures of samples during the test. In order to achieve the testing temperatures, specimens were placed inside the chamber at least 5 h before testing. The ITF was performed under the following conditions: a) controlled stress conditions at 25°C; b) stresses at 150 and 250 kPa levels; c) loading time of 0.1 and 0.4 s. Two failure criterions, were proposed to evaluate the endurance strength of the specimens, corresponding with permanent deformation and fatigue mechanisms. The first failure criteria were the minimum number of cycles required for the complete failure or 10% vertical deflection in the direction of vertical axis.

3.4 Indirect tensile-strength (ITS) test

In this test, a cylindrical specimen is loaded symmetrically through two loading strips. This which causes a semi-uniform tensile deformation along vertical axis (Fig. 4). The prevailing failure mode is fracture along this axis. With this test mixture susceptibility of asphalt mixtures, according to (AASHTO T-283) standard method were determined [32]. Bitumen cohesive strength and bond strength between aggregates and binder are the triggers of tensile strength of an HMA mixture. This can be achieved by maximum tolerable loading before cracking, Fatigue behavior and thermal cracking resistance could be improved with increased tensile strength of the specimens. Tensile strength is calculated from maximum load that a sample can undergo prior to cracking. Mixes with greater tensile strength provide better resistance to fatigue and thermal cracking. Six compacted dry and wet specimens, with air voids contents ranging between 6.5% and 7.5%, were chosen for the testing. First, vacuum is applied to partially saturate specimens to a level between 55% and 80%. Vacuum-saturated samples then were kept under a freeze-thaw cycles consisting of −18°C for +16 hours and then +60°C water bath for 24 hours. After this period, the specimens are considered conditioned. The other three samples remained unconditioned. Loading rate in this test was 2 in/min (approximately 50.8 mm/min).The failure load of each specimen was determined in controlled stress condition. ITS results of the specimens were determined from Eq. (2) below.

$$ITS = \frac{2F}{T\pi D} \quad (2)$$

where ITS is the indirect tensile stress (kPa), F is the failure load (kN), T is the sample thickness (mm), and D is the sample diameter

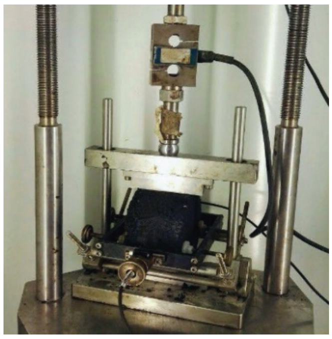

Fig. 3. UTM-14 testing machine under ITF testing.

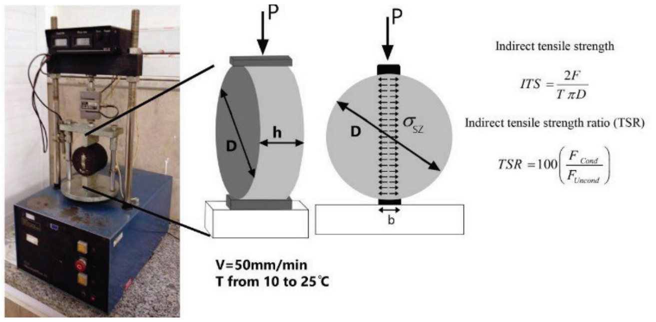

Fig. 4. Indirect tensile-strength test piece and sample schematic.

(mm). The indirect tensile strength ratio (TSR) was determined from the following equation:

$$TSR = 100\left(\frac{F_{Cond}}{F_{Uncond}}\right) \quad (3)$$

where F_{cond} and F_{uncond} are the indirect tensile strength of the conditioned and unconditioned samples, respectively. Fig. 4 shows the set-up of the test in study.

4. Results and discussion

4.1 Properties of the coarse recycled concrete aggregates

Physical properties of the mineral (natural) aggregate, RCA and treated RCA were evaluated applying various tests. Results are reported in Table 5. As it can be seen these table, treatment effectively enhanced physical and mechanical properties of RCA. The results indicate that the improving rate of physical and mechanical enhancement of RCA in the first surface treatment (aggregates soaked in acid) is much more than the second treatment (CM Slurry). This is probably due to the fact that the weak part of RCA in the first surface treatment had been gone. According to the overall results which is obtain in Table 5 , the surface treatment method proposed in this present work is considered to be a reliable new technique that can improve the quality of RCA.

4.2 Surface morphology and mineralogy analyze

The surface morphology and texture of RCA and NA materials are shown in SEM photos (Fig. 5). As shown in this figure, the recycled aggregate surface is more porous compared with NA aggregates. It was observed that the adhered mortar was wide

Table 5
Properties of the various aggregates.

Test	Standard methods	Size	Natural aggregate	Untreated RCA	Step one: Acid treated	Step two: CM treated
Specific gravity (g/cm^3)	BS812, Part 2	10mm	2.67	2.39	2.51	2.52
Water absorption (%)	BS 812,Part 2	10mm	0.81	5.32	4.41	4.36
Abrasion loss (%) (Los Angeles)	ASTM C131	Grading B	35	45	39	37
Flatness particles (%)	ASTM D4791	Random	12	15	13	13
Elongation particles (%)	ASTM D4791	Random	13	16	15	15
Aggregate Impact Value (AIV)	BS812, Part 112	14mm	14	23	20	19

spread at different thicknesses on the surface of RCAs. The high magnification clearly showed presence of various voids and particles with diverse shape and size. This explains the higher water absorption and lower density of RCAs compared with NA. In fact with reference to Table 5 it can be observe that RCAs has a high water absorption and low density. It can be seen in the Fig. 5 that there is a significant difference between the surfaces of RCA and natural aggregate. In addition, there is a considerable difference between the degree of roughness of the RCA and the natural aggregate. Roughness was disappeared broadly from RCA surface due to the acid treatment action as shown in Fig. 6(a). It can be observed that acidic solutions have attacked the surface and have dissolved adhered mortar. Hence, this method can be considerable method for removal of adhered mortar. On the other hand, when the surface of RCA is cleaned by acidic solution and all the loose cementitious materials were removed, the inside pores become more visible. Now the second stage begins. At this stage, the surface of treated RCA is coated with needle shaped CM, not only because of the filled aggregate surface pores, but due to the increased of aggregate strength and bridging action between cracks in the adhered cement mortal of RCA. The needle-shaped particles of calcium metasilicate and its dispersion are shown in Fig. 6(b). The recycled aggregate surface is more porous compared with NA aggregates. It was observed that the adhered mortar was wide results of EDAX analysis for two-stage treated RCA are shown in the Fig. 7. The findings represent spectrum analysis for chemical and mineral composition of treated RCA through EDAX quantification. For treated RCA, the EDAX analysis clearly showed that the predominant elements are oxygen, calcium and silicon which are the main components of CM.

4.3 ITF testing results

In pavement engineering, fatigue life determines how long the bitumen withstands cyclical loads (i.e. traffic loads) before the failure occurs. This is defined as the maximum number of cycles

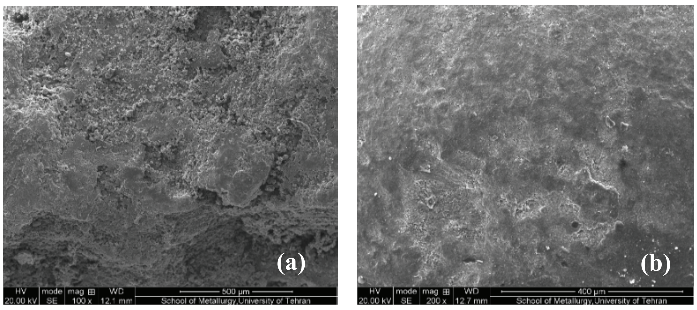

Fig. 5. Surface characterization of (a) RCA and (b) NA aggregates.

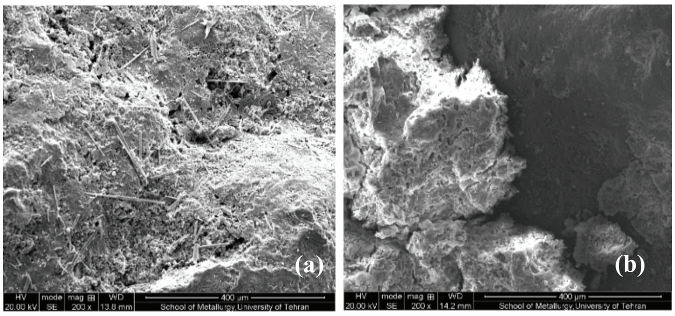

Fig. 6. Surface evaluation of (a) CM and (b) acid treatment.

to complete failure. ITF testing was performed at two fixed stress levels of 150 and 250 kPa, at room temperature. The N-S plot (Fig. 8) evaluates the goodness of fit of the fatigue life law equations and the testing results on a logarithmic scale. The high correlation coefficient (R2) values suggest a significant statistical relationship between fatigue life law equations and the results obtained by tested specimens. The influence of RCA addition has been significant on fatigue behavior of asphalt mixtures on the tested specimens. The maximum increase of the fatigue life was obtained by adding 50% RCA. Due to significant positive relationship between the RCA content and stiffness [33], the lower percentages of RCA (25%) leads to less fatigue life of asphalt mixtures.

The results showed the effectiveness of using RCA in improving fatigue life of asphalt mixtures. However, there is a scant difference between treated and untreated RCA mixes. Fig. 8 indicates that the RCA mixtures have a little higher fatigue performance as the control mixture. As mentioned before, there is a significant correlation between the initial strain and fatigue performance of the mixtures. Therefore, at constant stress, using treated RCA aggregate in asphalt mixture leads to approximately 10% improvement in fatigue performance while for untreated mixes this improvement was about 8%. In addition, Fig. 8 illustrates that HMA made with treated RCA displayed similar

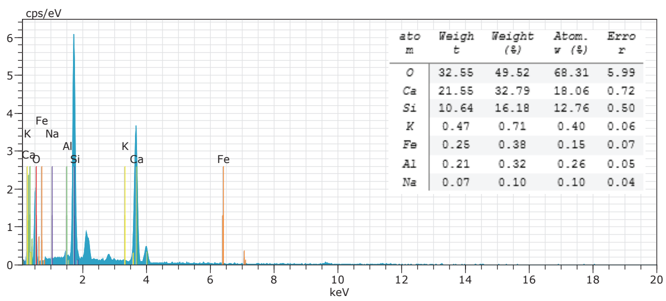

Fig. 7. EDAX of treated RCA.

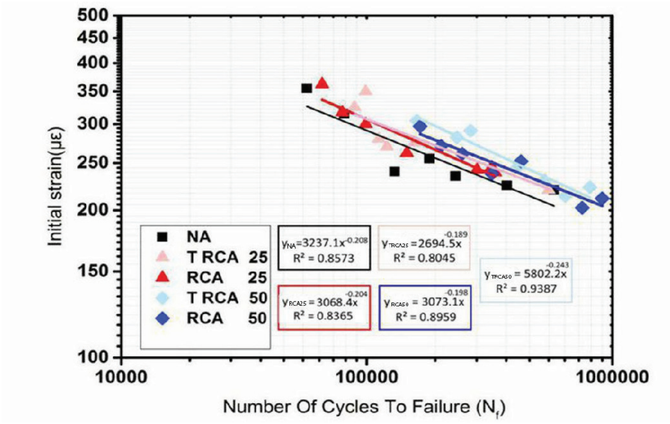

Fig. 8. Fatigue life of all mixtures containing RCA.

slopes in their fatigue life laws regardless of the RCA percentage used. For low and high initial micro-strains, mixtures made with untreated RCA had lower fatigue life than mixtures made with treated RCA.

4.4 Moisture susceptibility

The tensile strength of specimens containing different amounts of RCA and their TSR values are shown in Figs. 9 and 10, respectively. Fig. 9 shows the inverse relationship between tensile strength and the number of freeze–thaw cycles of tested materials. There is also an inverse relationship between tensile strength and the RCA content of mixes. Due to low cohesive properties of RCA aggregates covered with bitumen, high permeability of the mortar and low Los Angles abrasion values of RCA, treated and untreated RCA asphalt mixtures exhibited poor water resistance. When the RCA is treated by the two-step treatment processes, the loose and weak parts of hydrated cement adhering to the aggregate particles are removed and the surface pores are filled with fine particles. This process reduces permeability of the mortar and increase Los Angles abrasion values of RCA. Therefore, as it can be seen in Fig. 5, the result indicate that moisture susceptibility of treated RCA materials exhibit generally are better that untreated RCAs.

TSR results of the treated and untreated RCA mixes are compared as it can be seen in Fig. 10. The treated RCA has a greater moisture damage resistance and lower water sensitivity. Generally, the addition of RCA aggregates to mixture leads to lower ITS values, cohesion between aggregate particles and surfaces. Although improvements in HMA containing treated RCAs were insignificant, this enhancement seems to be acceptable. As it is asphalt mixtures can be observed, while for treated RCAs this is only 5% (TRCA50%). These treatment minimize the adverse effect related to the inherent low quality of RCA products which can be seen in Fig. 10. The significant improvement in the use of treated RCA, as demonstrated in this study, enables its application in HMA mixes with less detriment to asphalt performance in terms of moisture susceptibility.

5. Conclusions

This paper was intended to investigate the impact of Recycled Concrete Aggregate (RCA) on mechanical properties of asphalt mixtures. Asphalt mixtures prepared contained 25 and 50 percent of RCA with their size ranging from 4.75 to 19 mm. In order to improve the quality of mixes, RCAs were treated in hydrochloric acid (HCl) and Calcium Metasilicate (CM) slurry prior to mixing process. In order to investigate the physical characteristics of RCAs various laboratory tests were used. Fatigue performance and moisture susceptibility of mixes were also evaluated. Results of this study can be summarized below:

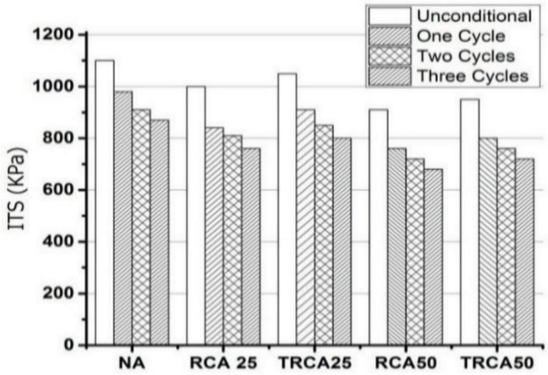

Fig. 9. Indirect tensile strength of asphalt mixtures containing different amounts of RCA.

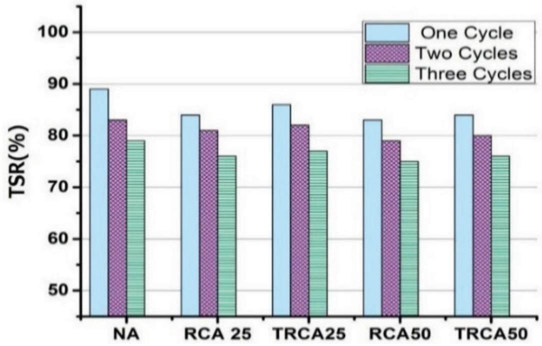

Fig. 10. TSR values of asphalt mixtures containing different amounts of RCA.

The results showed that these treatment methods can successfully improve the quality of RCAs and allow for increasing the usage of these waste materials in construction projects which has positive effect on environment. Despite the fact that this treatment method has a multi-step process, fortunately this method does not require complicated mechanical equipment and high energy consumption. It should be noted that the use of these treatments in enhancing the quality of RCAs in large-scale projects requires further investigation and research, which will probably be addressed in future research.

The results obtained by ITFT showed that using RCAs improved the fatigue behavior of mixtures by increasing fatigue life and decreasing final strain. In addition, there was no notable difference between the fatigue life of untreated and treated RCA asphalt mixtures.

Hot mix asphalt containing RCAs showed to have better fatigue performance than conventional mixes containing natural mineral aggregates. A mix containing higher percentages of RCAs has a longer fatigue life.

Asphalt mixes containing RCA materials showed some moisture susceptibility. This was recognized to be the result of siliceous nature of RCAs used in this research. The results indicated that by treating RCAs, moisture susceptibility of treated RCA mixes could be improved.

Asphalt mixtures with higher RCAs exceeded the specification limit of moisture damage, so it is recommended that asphalt mixtures be used either in arid climates or in any climates if it is determined that there is no probability of moisture damage by assessing moisture susceptibility.

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