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Research Article

Effects of Crumb Rubber Size and Concentration on Performance of Porous Asphalt Mixtures

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The purpose of this study is to investigate the effect of size distribution and concentration of crumb rubber on the performance characteristics of porous asphalt mixture. The recycling of scrap tires in asphalt pavements appears as an important alternative providing a large-scale market. The characteristics of bitumen are very important with regard to service life of porous asphalt pavement. The experimental study consists of two main steps. Firstly, the mixture design was performed to determine the optimum bitumen content. In the latter step, the mixtures were modified by dry process using crumb rubber in three different grain size distributions of #4~#20, #20~#200, and #4~#200 and rubber content of 10%, 15%, and 20% as weight of optimum bitumen. The permeability, Cantabro abrasion loss, indirect tensile strength, moisture susceptibility, and resilient modulus tests were carried out on the specimens. Test results show that #20~#200 sized rubber particles reduced air voids and coefficient of permeability, while they increased the Cantabro abrasion loss. In general, increasing the crumb rubber size and content decreased the performance characteristics of the porous asphalt mixtures.

1. Introduction

The worn-out tires from vehicles leave billions of waste tires every year becoming a significant source of waste materials. Scrap tires are still a serious environmental and financial issue for many countries in the world occupying landfill spaces and becoming a threat for health and safety hazards to the community. The scrap tires consist of rubber, carbon black, steel, and so forth potentially to be very useful in various applications which have been evaluated effectively as a valuable resource. There are some different recycling strategies developed for waste tires. The main markets in the assessment of waste tires include tire-derived fuel (TDF), civil engineering applications, and ground rubber. The recycling of waste tire has a good trend. However, it has still potential to consume more waste tires. In addition, TDF corresponds to 54% of the total scrap tires which may not represent an ideal application in the current recycling methods for waste tires from environmental conservation perspective [1]. More value-added alternatives are required to be discovered in order to motivate public and private agency to recycle them.

One of the approaches of recycling scrap tires is to use crumb rubber from the tires as a component in asphalt pavement mixtures. The crumb rubber is combined in asphalt mixtures to improve the performance of asphalt concrete pavements. The large-scale usage of crumb rubber from waste tyres in asphalt mixtures appears to be more feasible alternative in terms of engineering applications and environmental consideration. Asphalt-rubber pavements can minimize environmental impact and maximize the conservation of natural resources.

The ability of crumb rubber to improve the asphalt mixture performance depends on many factors such as the mixing methods, reaction time with bitumen, nature of the rubber, and size and concentration of the rubber particles. There are two different processes using crumb rubber in the asphalt mixtures, a dry process and a wet process. In the wet process, the finer crumb rubber is mixed with asphalt cement at high temperature. It reacts with the bitumen and creates modified bitumen. In the dry process, the crumb rubber is mixed together with the aggregates prior to the addition to the asphalt. During dry process in which the crumb rubber

is used as an aggregate, the chemical reaction between crumb rubber and bitumen is quite limited [2].

The advancement in hot-mix asphalt pavement technology resulted in the development of a different type of asphalt mixture. Porous asphalt is used widely as an application of pavement surface in Europe. Porous asphalt or open-graded asphalt concrete is an environmentally friendly road material which was developed by using advanced technology in hot-mix asphalt mixture design. It is used effectively in regions with the highest level of precipitation. The porous asphalt used as surface layer mostly has an air void content of 20% and can improve the ride quality for drivers during wet weather by reducing skidding. This pavement system prevents hydroplaning and spraying on the road surface and improves visibility by eliminating the light reflected from the road surface. The porous asphalt mixture is designed by using a relatively large proportion of coarse aggregates (more than 80%) with few fine aggregates to create a large space for water drainage. It also significantly reduces traffic induced noise emissions by means of the high porosity [3]. The selection of asphalt binder with high viscosity is an important issue on account of the specific structure of its high void content in the mixtures. To improve the durability of porous asphalt mixtures, polymer-modified bitumen was recommended to be used in moderate and hot climates with heavy traffic [4].

Modified bitumen with polymers and synthetic and natural rubber used in porous asphalt surfaces significantly reduce the level of noise from vehicles compared with the dense graded asphalt surfaces [5]. The use of polymer-modified or rubberized binders instead of unmodified binder in the 4.75 mm open-graded mixture reduced permeability but increased acoustic absorption. Mixtures containing rubberized bitumen show the most acoustic absorption improvement [6]. One advantage of using rubber modified asphalt is that it raises the viscosity of the bitumen and provides increase of the bitumen content in the mixture. Thus, massive asphalt film surrounding the aggregate enhances durability of the asphalt mixtures. The open-graded asphalt with asphalt-rubber binder had significantly reduced not only moisture sensitivity but also superior fatigue resistance and cracking as compared to traditional porous or semiporous asphalt mixtures [7, 8]. A previous study claim that Large Stone Porous Asphalt-Rubber Mixture has better performance than conventional large stone porous asphalt mixture using polymer-modified asphalt, and it could be used as stress absorbing layers of semirigid base asphalt pavement [9]. Moreover, the experimental results of repeated triaxial-loaded and wheel tracking permanent deformation tests confirmed that the asphalt-rubber porous mixtures have superior performance against rutting [10]. Several studies have shown that rubber content between 10% and 30% of the bitumen improves resistance to moisture damage, the susceptibility to temperature, and the tendency to flow [11, 12]. The particular facts of performance evaluation of test sites in Florida indicated that the wet process addition of asphalt-rubber blended into the bitumen improved the cracking resistance of the surface mixtures [13]. The characteristics of the crumb rubber can influence properties of asphalt rubber such as rubber quantity in the blend and particle size distribution. Additional factors include crumb rubber surface area, grinding process, crumb rubber chemical composition, and contaminants as water, fibre, and metal [14].

Considering the preceding information from the literature, this study was designed to examine the effects of the content and size of crumb rubber on the porous asphalt mixture performance.

Table 1: The physical properties of coarse aggregate.

Properties	Specification	Results	Specification	
			Min.	Max.
Los Angeles abrasion (%)	ASTM C131	13.5	—	30
Sodium sulfate soundness (%)	ASTM C88	0.64	—	12
Percent fractured faces (%)	ASTM D5821	100	100	—
Flakiness index (%)	BS 812	20	—	25
Polish value	ASTM C3319	53	50	—
Stripping resistance (%)	ASTM D1664	60–65	—	50

Table 2: Test results on aggregate specific gravity and absorption properties.

Properties	Course aggregate	Fine aggregate	Filler
Bulk specific gravity	2.586	2.639	—
Apparent specific gravity	2.735	2.763	2.782
Water absorption (%)	2.1	1.7	—

2. Experimental Program

This section includes material characterization of basalt aggregate, bitumen and crumb rubber, and test methods such as permeability, Cantabro abrasion loss, indirect tensile strength, moisture susceptibility, and resilient modulus tests.

2.1. Materials Characterization. Crushed basalt aggregates and conventional bitumen of penetration grade 50/70 were used in this experimental study. Also, crumb rubber obtained from waste tires was used as a modifier in different sizes and concentrations. The characterization tests conducted in the laboratory were given in this section.

2.1.1. Aggregate. High-quality aggregates are required to provide the field performance of the large-void porous asphalt during the service life. In this study, one type of crushed basalt aggregate was used as coarse and fine aggregate. Also, stone dust which was obtained from the same basalt aggregate was used as the filler material. The basalt aggregate was provided from a quarry in Eskişehir, Turkey. The main physical properties of the coarse aggregate with the criteria are given in Table 1. The aggregate specific gravity and absorption test results were shown in Table 2.

The aggregate gradation for porous asphalt mixtures was selected between broad bands (boundary lines) according to Porous European Mix (PEM) Specification. The aggregate gradation is given in Figure 1.

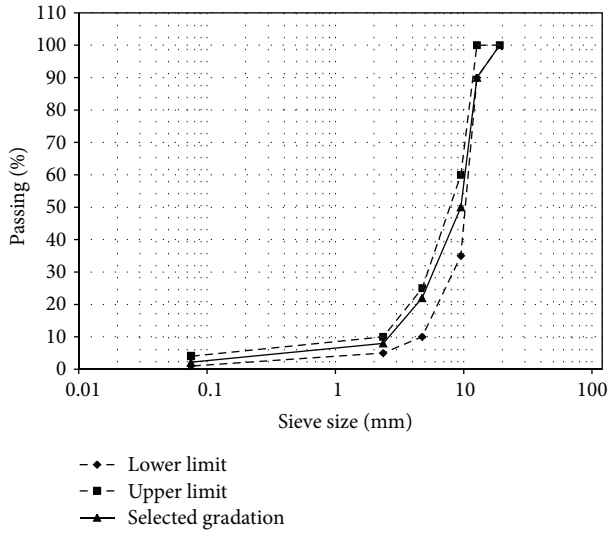


Figure 1: Aggregate gradation of porous asphalt mixture with specification limits of PEM.

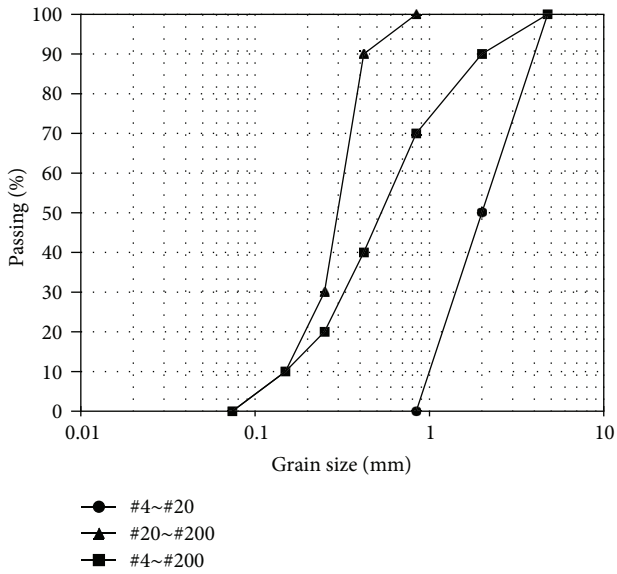


Figure 2: Grain size distributions of crumb rubber.

Table 3: Physical properties of conventional bitumen.

Properties	Specification	Results
Penetration at 25°C, 100 g, 5 s (0.1 mm)	ASTM D5	63
Softening point (°C)	ASTM D36	49
TFOT residue	ASTM D2872-04	
Mass loss (%)	ASTM D2872	0.096
Retained penetration (%)	ASTM D5	37
Softening point after hardening (°C)	ASTM D36	61
Flashing point (°C)	ASTM D92	240
Specific gravity at 25°C	ASTM D70	1.021

2.1.2. Bitumen. Bitumen from one source was used in this study. The penetration grade bitumen of 50/70 obtained from the Asphalt Production Refinery is widely used in Turkey. This type of asphalt binder was chosen instead of modified bitumen so that effect of the crumb rubber on porous asphalt mixtures could be clearly determined. Table 3 gives physical properties of the bitumen.

2.1.3. Crumbed Rubber. The crumb rubber was obtained from tire buffing process. It includes removing the worn tread by a special machine and applying a new tread. The different sizes of rubber were separated by sieves. The grain size distributions of crumb rubber were given in Figure 2. The grain size distribution group of #4~#20, #20~#200, and #4~#200 includes different sizes of rubber particles. Figure 3 represents a general appearance of each group. Even though Figure 3 gives some information about the form of #4~#20, the forms of small particles such as #100~#200 mesh size cannot be determined from it. Therefore, Scanning Electron Microscopy (SEM) images of the crumb rubber in Figure 4 were presented. The fiber-like shape of the pine needle rubber can contribute to reinforcing the porous pavement and decrease the bitumen drain down.

2.2. Test Methods. The test program in this study consisted of two steps. Step I covered the mix design of porous asphalt mixtures. Step II was to investigate the effect of crumb rubber concentration and size on design and performance characteristics of the porous asphalt mixtures.

The principle design of porous asphalt mixtures is to determine the bitumen content that will optimize its engineering properties in relation with the in-service behavior during pavement life. The Porous European Mix Specification including the tests of air void, permeability, particle loss resistance (Cantabrian), and indirect tensile were used to determine the optimum bitumen content. In addition, performance-related tests such as moisture susceptibility and resilient modulus tests were conducted on the porous asphalt mixtures with and without crumb rubber.

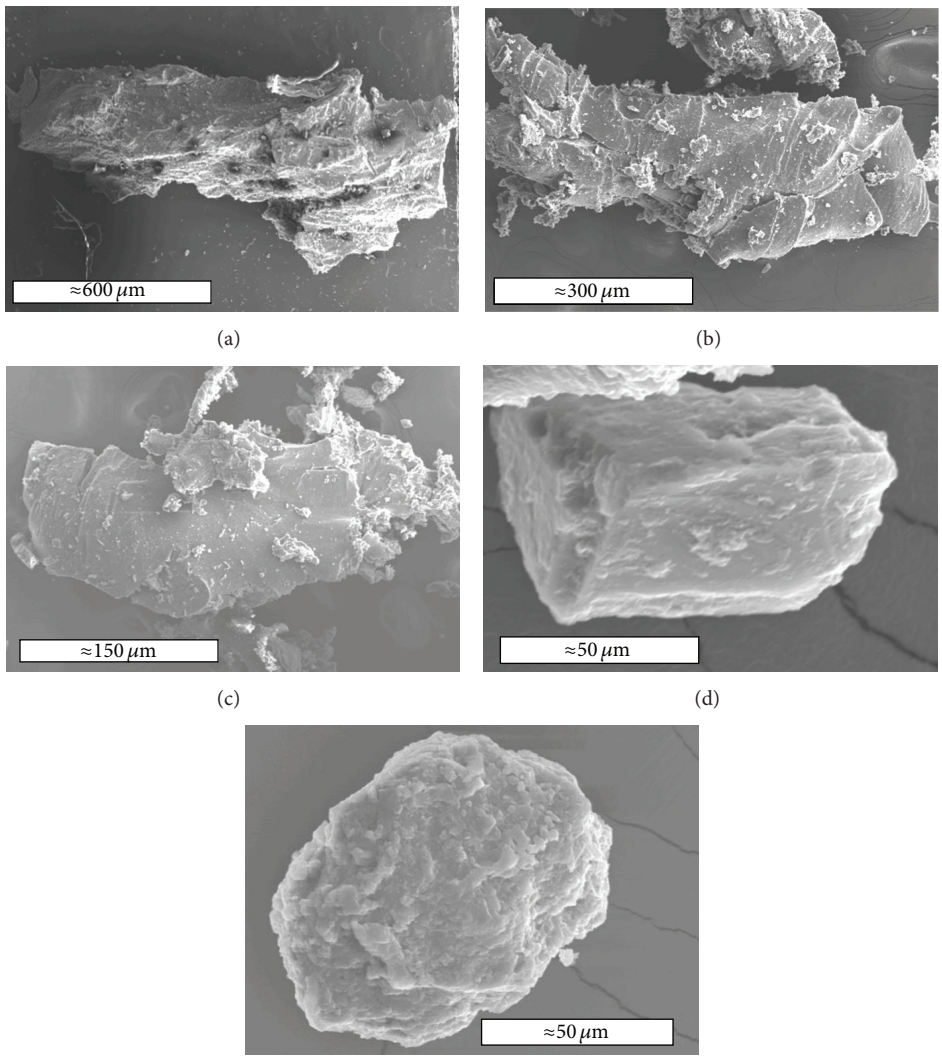
2.2.1. Mixing and Production. Each specimen was comprised of about 1200 g of aggregate batches and bitumen. Modified specimens were prepared by dry process in which crumb rubber was added in the aggregate batch and mixed for 2 minutes. The aggregates and asphalt binder were blended at their corresponding mixing temperatures. A compaction process was followed subsequently by applying 50 blows on each face of the specimen using the standard Marshall hammer.

2.2.2. Air Voids Determination. To provide sufficient permeability in the porous asphalt mixtures, an air void content ranging between 16% and 22% (or greater) is recommended [15, 16]. The air void percentages of the porous asphalt specimens were very difficult to determine due to the higher porosity. This test procedure determines the bulk specific gravity of specimens of compacted asphalt mixtures. In this method, compacted specimens were coated with paraffin



(a) (b) (c)

Figure 3: Appearance of crumb rubber particles: (a) #4~#20; (b) #20~#200; (c) #4~#200.



(a) (b) (c) (d) (e)

Figure 4: Scanning Electron Microscopy (SEM) pictures for different sizes of crumb rubber particles: (a) #4~#20; (b) #20~#200; (c) #4~#200; (d) #100~#200; (e) #100~#200.

film, and then the bulk specific gravity with regard to the procedure in AASHTO T275 [17] was determined.

2.2.3. Hydraulic Conductivity Test. Hydraulic conductivity is a significant characteristic of porous asphalt mixtures on account of designing a drainage layer in pavement structures. The hydraulic conductivity of the compacted specimens symbolized in terms of the coefficient of permeability (k) was determined by using a falling-head water permeameter. The apparatus of falling-head permeability test consists of a metal cylinder and demountable metal plates at the top and bottom of the metal mold. The top plate has a hole with at least 31.75 mm inner diameter of graduated pipe for water inflow, and the bottom plate has an a outlet hole of minimum inner diameter of 18 mm and valve so that water can flow out. The specimen in the mold was placed between the bottom plate and the top plate and compressed by using clamps for sealing the bottom and top plates. The graduated pipe is filled with distilled water, and the valve is opened to flow through a saturated specimen. The time period taken for level change of water between two fixed points on the perspex pipe was recorded. The coefficient of permeability is then determined based on Darcy's law. A minimum permeability coefficient of 10^{-2} cm/s (≈100 m/day) is commonly recommended for the pervious pavement structure [18, 19].

2.2.4. Cantabro Abrasion Test (Particle Loss Resistance). The Cantabro test was conducted to evaluate the resistance to particle loss of the mixtures according to ASTM D7064 [20]. The compacted specimens were individually put in the Los Angeles testing machine without steel balls. After Los Angeles drum had been rotated for 300 revolutions at a speed of 30–33 revolutions per minute, the loose material broken off from surface of the test specimen was discarded. The masses of the specimens before and after the test were recorded. The percentage loss by weight of original specimen was calculated as the Cantabro abrasion. The percentage of Cantabro abrasion must be less than 25% in the European Specification.

2.2.5. Indirect Tensile Strength Test. The indirect tensile (IDT) strength test has been widely used for hot-mix asphalt (HMA) mixture design. The splitting strength is determined in this test as an indicator of the tensile strength of the compacted specimen. The results of (IDT) strength are employed to obtain the comparative relative strength of asphalt mixtures and predict the potential for pavement distress. Since the performance of porous mixtures depends on tensile strength of bitumen film, the IDT strength is also an important characterization test for porous asphalt mixture. The test is performed by using Marshall stability test equipment at 50 mm/min deformation rate and 25°C temperature in accordance with ASTM D6931 procedure [21]. In the test, a cylindrical specimen is exposed to a compressive load. It acts along the vertical diameter plane by a curved loading strip. The developed tensile stress, perpendicular to the direction of the applied load, ultimately causes the specimen to fail by splitting along the vertical diameter. The ultimate load at failure is recorded and used to calculate the IDT strength of the specimen.

2.2.6. Moisture Susceptibility. Moisture causes a loss of adhesion between the bitumen and the aggregate surface and accelerates the process of distresses such as rutting, cracking, and raveling in the asphalt mixture. Moisture susceptibility is extremely an important characteristic for the performance of the porous asphalt mixtures exposed to water damage. The test was performed according to Modified Lottman Test (AASHTO T283) that is one of the most largely used procedures for determining HMA water damage [22]. Six compacted specimens are required at 6%–8% air voids in the Modified Lottman Test. The specimens are separated into two groups. The first group of three is unconditioned specimens as the control group. The second group is conditioned specimens of vacuum-saturated saturation level between 55 percent and 80 percent. After conditioned specimens are placed in a freezer at −18°C for 16 hours, they are moved to at 60°C water bath for 24 hours. All of the specimens are subjected to the IDT strength test conducted with a loading rate of 50 mm/min at 25°C. The tensile strength ratio (TSR) is calculated by the average IDT strength of conditioned subset divided by the average IDT strength of control subset. The allowable value of TSR must be more than 70% for this test method.

2.2.7. Resilient Modulus (Stiffness Modulus) Test. Resilient modulus of asphalt mixtures is the most popular form of stress-strain measurement used to evaluate elastic properties. The five-pulse indirect tensile modulus test used to determine the stiffness of material was performed in accordance with ASTM D4123 [23] using Universal Testing Machine (UTM-5P). In the test, the cylindrical specimen is subjected to a pulsed diametric loading force, and the resulting total recoverable diametric strain is then measured at axes 90° from the applied force. Because the strain in the same axes is not measured, a value of 0.4 for Poisson's ratio of asphalt mixtures is accepted as a constant. The specimens were placed in the indirect tensile test equipment, and test results were recorded in the computer by data logger system. The test load sequence consists of 150 conditioning pulses and five-pulse test periods. The conditioning stage provides that the loading plates are seated onto the specimen for consistent results. The stiffness module is calculated by five-pulse test period. In addition, the specimen's skin and core temperatures were measured by transducers inserted in a dummy specimen located near the test specimen in order to control the testing temperature. In this study, specimens prepared in the laboratory were tested under the waveform type of Haversine at load pulse period of 3000 ms, pulse width of 80 ms, and peak loading force of 1000 N.

3. Test Result and Discussion

The results of porous asphalt mixture design were given in this section. In addition, the effects of rubber size and concentration on performance characteristics were discussed.

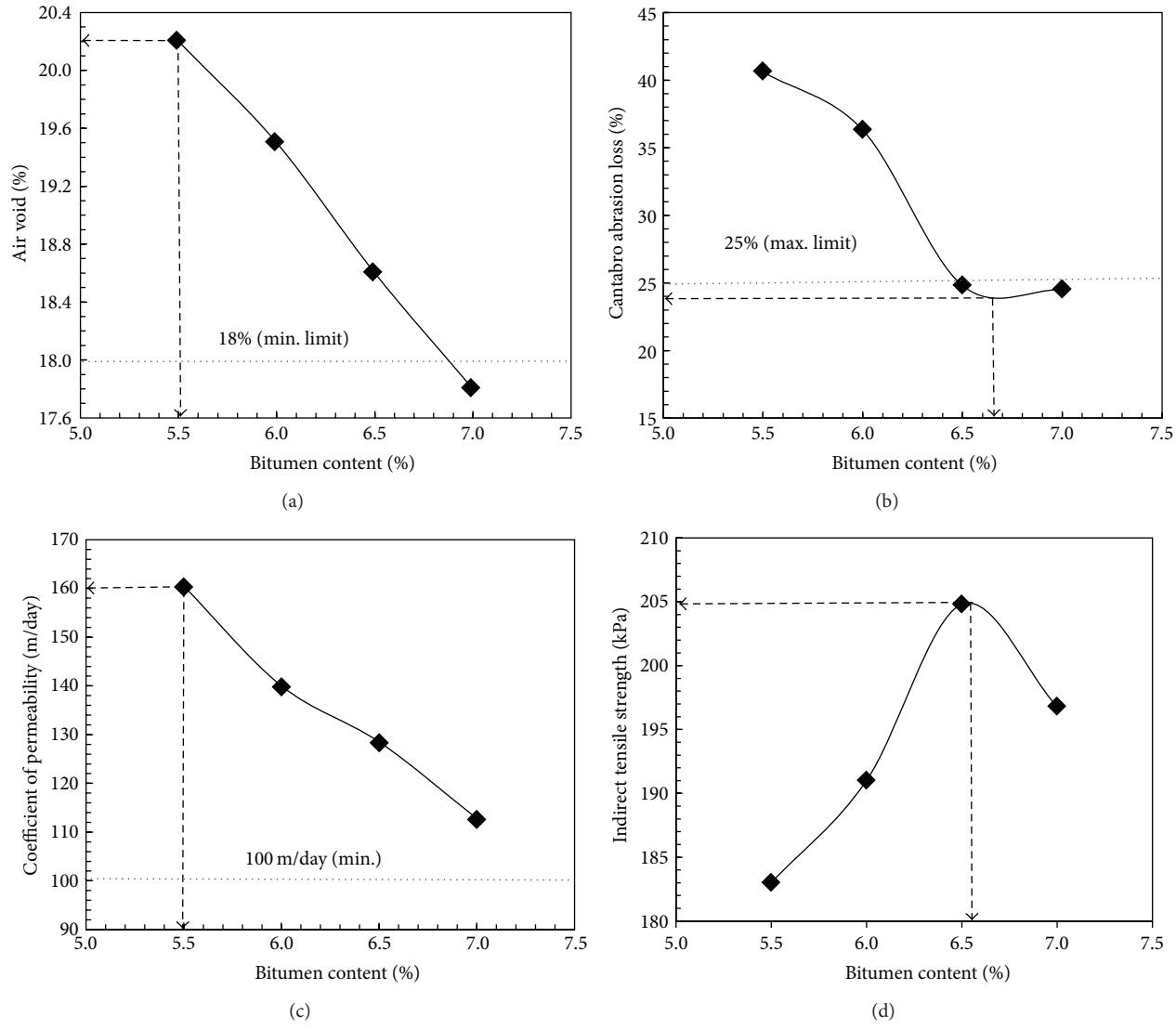


Figure 5: Graphics of mix design for porous asphalt mixtures: (a) air voids; (b) Cantabro abrasion loss; (c) coefficient of permeability; (d) indirect tensile strength.

3.1. Mix Design. European Porous Asphalt Mix Design Approach is generally based on determining the voids and the percentage of particle abrasion loss at various binder contents. The design bitumen content is optimized for air voids and abrasion. It is recommended that the modified bitumen is used to improve the resistance against particle loss. It achieved a longer durability by means of its higher cohesion and viscosity [4].

Porous asphalt design procedures used in Europe and America mostly include the air void ratio, permeability, Cantabro abrasion loss, and indirect tensile strength tests. In this study, the following design criteria widely accepted in these countries were selected. The minimum permeability coefficient depends on the target air voids (18–23%) and is 100 m/day. A maximum Cantabro particle loss of 25% is allowed at 25°C. The allowable asphalt content ranges 4–6 percent. The bitumen content ensuring these limit values was selected as a percentage of optimum bitumen. The graphics of the mix design were given in Figure 5.

The air void and permeability coefficients were decreased by increasing bitumen content (Figures 5(a) and 5(c)). The maximum values of these characteristics were obtained for bitumen content of 5.5%. The minimum Cantabro abrasion loss provided the bitumen content of 6.5%. However, test result at bitumen content of 7% is quite close to results at 6.5% as shown in Figure 5(b). The maximum value for indirect tensile strength was also obtained for bitumen content of 6.5% as shown in Figure 5(d). The optimum bitumen content of 6.5% was determined according to these results. All design values of porous asphalt mixture were given in Table 4. Although the mix design of porous asphalt mixture was achieved, design requirements with the penetration grade

Table 4: Result of the Porous Asphalt Mix Design.

Design characteristics	Results
Optimum bitumen, %	6.5
Air void, %	18.6
Cantabro abrasion loss, %	24.8
Coefficient of permeability, m/day	128.5
Indirect tensile strength, kPa	204.8

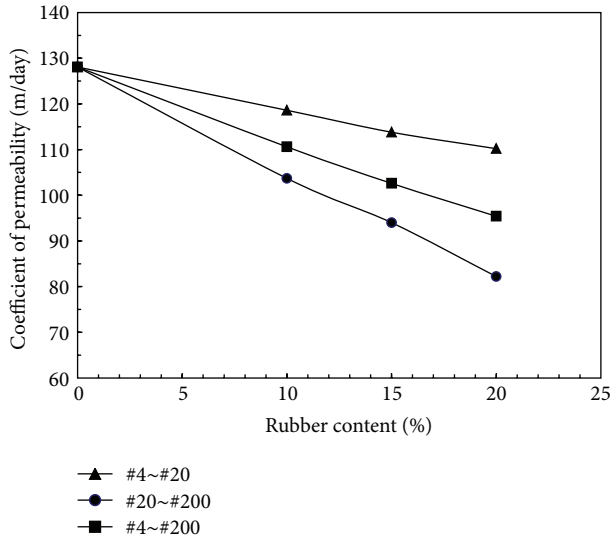


Figure 6: Effect of crumb rubber size and content on coefficient of permeability.

bitumen of 50/70, the low values in Cantabro abrasion loss, and IDT strength test were introduced due to the necessity of modified bitumen.

3.2. Effect of Crumb Rubber on Performance Characteristics. The effects of crumb rubber size and content on performance characteristics of porous asphalt mixtures were analyzed and discussed in this section.

3.2.1. Hydraulic Conductivity. Figure 6 illustrates the variations of permeability coefficient with rubber content for all three sizes (#4~#20, #20~#200, and #4~#200). Increasing the content of the crumb rubber significantly reduced the coefficient of permeability. Analyzing the crumb rubber in terms of particle size, it was indicated that #4~#20 rubber size had the maximum value of permeability coefficient. The addition of crumb rubber remained below limit value of permeability coefficient (100 m/day) except in the case of the 10% content of the #20~#200 crumb rubber. For #4~#200 crumb rubber, the addition of 20% crumb rubber similarly remained below limit value of 100 m/day. In all other cases, coefficient of permeability was provided over the limit value. These results show that the small size of rubber particle reduced air voids and the coefficient of permeability due to its surface area.

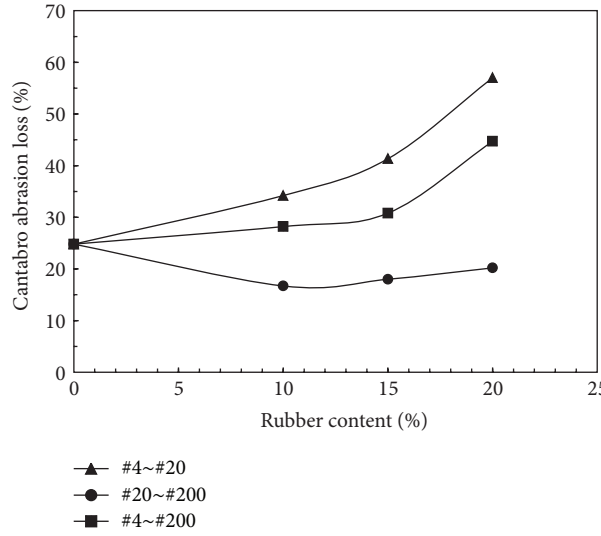


Figure 7: Effect of crumb rubber size and content on Cantabro abrasion loss.

3.2.2. Cantabro Abrasion Loss. The experimental results were analysed as given in Figure 7. It can be clearly seen that Cantabro abrasion loss was achieved less than control specimens in the case of all contents of the #20~#200 crumb rubber. The addition of 10%, 15%, and 20% rubber content of #20~#200 showed an improvement of 19%, 27%, and 33%, respectively, compared to control. Particle loss of mixtures increased as the content of rubber increased for all rubber particle sizes. The optimum rubber concentration of 10% was determined. The degree of particle loss in the mixtures with #4~#20 and #4~#200 was observed to increase in comparison with control specimens. This increase of 130% reached at 20% content of #4~#20 rubber sizes in which the maximum particle loss occurred. #20~#200 mesh size include finer particles in comparison to the other mesh size (Figure 3). Finer rubber particles formed homogeny and rigid matrix (bitumen-fine aggregate, crumb rubber) due to the fact that they were uniformly mixed in the asphalt mixture. Because the coarse rubber particles in #4~#20 and #4~#200 mesh sizes caused increasing discontinuity in the bitumen film, it weakened the strength of the bitumen film. In addition, the #20~#200 mesh size increased the surface area which required surrounding particles by bitumen. Thus, decreasing bitumen film thicknesses tended to improve tensile strength of porous asphalt mixtures. As a result, Cantabro abrasion loss values decrease by using #20~#200 crumb rubber.

3.2.3. Indirect Tensile Strength. The indirect tensile (IDT) strength test is very useful in deciding the performance of porous asphalt mixtures which depend on the cohesion of bitumen film. The variations of indirect tensile strength with rubber content for all three sizes are given in Figure 8. IDT strength test results were in compliance with Cantabro abrasion test results. The addition of crumb rubber significantly reduced the IDT strength except in the case of the 10% content of the #20~#200 crumb rubber. The case was the only one

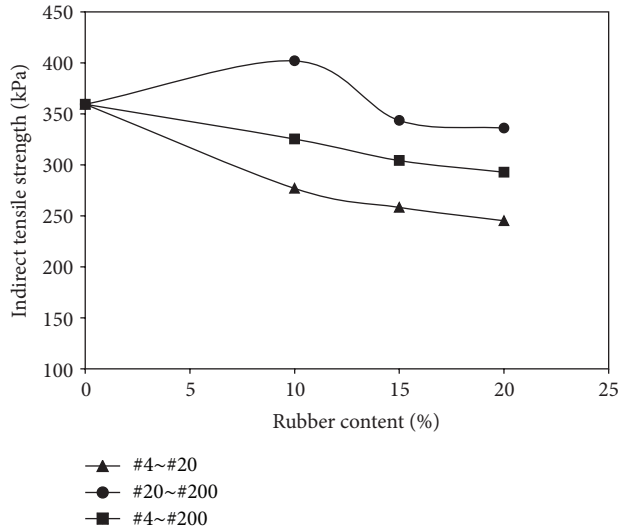


Figure 8: Effect of crumb rubber size and content on indirect tensile (IDT) strength.

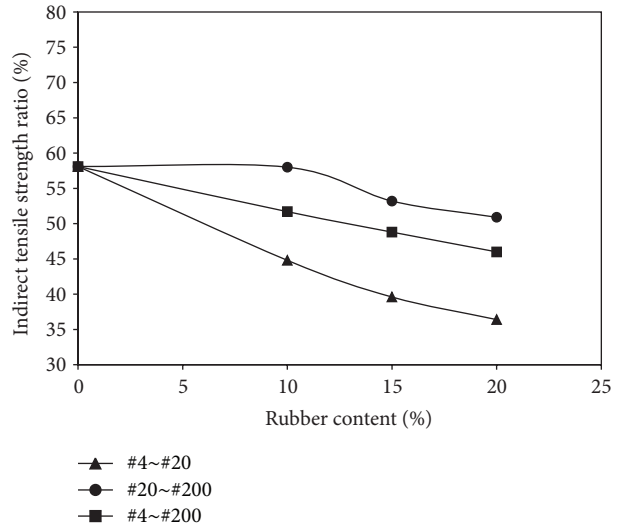


Figure 9: Effect of crumb rubber size and content on moisture susceptibility.

combination which increased the indirect tensile strength by 12% compared to the control specimens. IDT strength values were less than the control specimens for all rubber contents of #4~#20 and #4~#200. The maximum reduction in IDT strength by 32% was obtained in the case of the 20% content of the #4~#20 crumb rubber. In general, increasing the crumb rubber size has decreased the IDT strength of the porous asphalt mixtures. These results can be explained by the fact that the strong matrix was formed by homogeneously mixing small rubber particles in the mixtures and maintained an adhesion between the bitumen and the aggregate. It can be concluded that the cohesion and IDT strength of the bitumen film were negatively affected by the form of rubber particle as shown in Figure 4. Although larger crumb rubber particle shaped like pine needle rubber improves indirect tensile strength of dense graded asphalt pavement [24], it affects the performance of porous asphalt mixtures negatively because the porous asphalt mixtures have less fine aggregate.

3.2.4. Moisture Susceptibility. The moisture damage in the asphalt concrete pavements is an important problem. The porous asphalt pavement is particularly subjected to moisture damage more than dense graded asphalt mixtures. The moisture damage counts on the loss of adhesion between bitumen and aggregate surface or cohesion of the bitumen. The modification of bitumen or mixture is the most commonly used method in the improvement of the resistance to the moisture damage.

The TSR value for the control specimens was determined to be 58%. This value remained below the limit value of 70% because unmodified bitumen was used to prepare the control specimens. The unmodified bitumen was preferred to be employed for a better understanding of the effect of crumb rubber on the porous asphalt mixtures. An examination of the graphical presentations in Figure 9; the addition of crumb rubber significantly reduced the TSR value except in the case of the 10% content of the #20~#200 crumb rubber. For #20~#200 crumb rubber, the addition of %10 crumb rubber has obtained a similar TSR value with control specimens. TSR values were less than the control specimens for all rubber contents of #4~#20 and #4~#200. Increasing the crumb rubber size has substantially decreased the TSR values. The maximum reduction in TSR by 63% was obtained from the addition of the 20% content for the #4~#20 crumb rubber. As explained above, while the mixtures with small rubber particles improved performance of porous asphalt, the big size rubber particle negatively affected cohesion of bitumen and IDT strength. This effect increased largely the IDT strength of conditioned specimens. Therefore, the TSR values are significantly reduced compared to the control specimens.

3.2.5. Resilient Modulus. The resilient modulus measured in the indirect tensile mode represents the elastic properties of asphalt mixtures under repeated load effectively. The resilient modulus was one of the most commonly used methods for measuring the stiffness modulus of hot-mix asphalt. The variations of resilient modulus with rubber content and rubber size were given in Figures 10 and 11, respectively. The addition of crumb rubber reduced the resilient modulus except in the case of the 10% and 15% contents of the #20~#200 crumb rubber. The maximum resilient modulus value was obtained in rubber content of 10% at #20~#200. In this case resilient modulus was increased by 22% compared to the control specimens. Increasing the crumb rubber size reduced the resilient modulus of the porous asphalt mixtures substantially. The maximum decrease in resilient modulus of 56% was determined in rubber content of 20% for #4~#200 crumb rubber. Resilient modulus values were decreased as crumb rubber content in the mixtures for all rubber particle sizes. The optimum content of crumb rubber was determined in 10%. This test results coincided with IDT

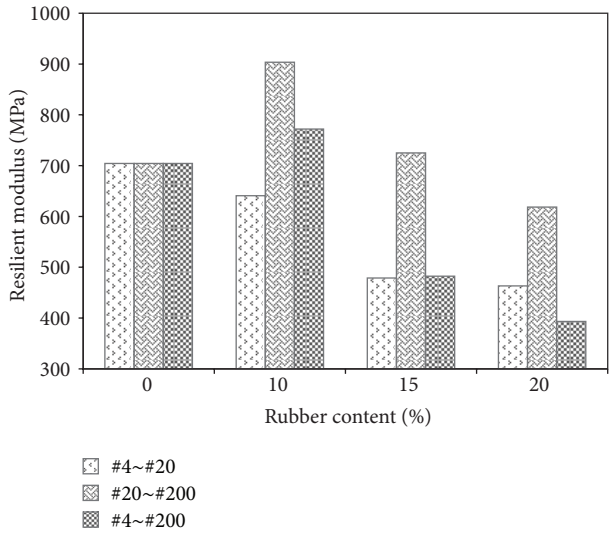


Figure 10: Effect of crumb rubber content on resilient modulus.

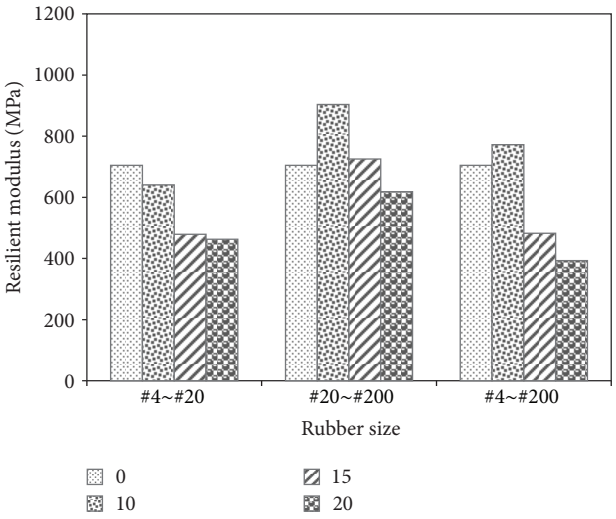


Figure 11: Effect of crumb rubber size on resilient modulus.

strength and Cantabro abrasion test results. Therefore, the impact of crumb rubber size and content on resilient modulus can be interpreted as noted above.

4. Conclusion and Recommendation

This study presented an evaluation of recycled scrap tire obtained from tire recapping or tire buffing in the porous asphalt mixtures. The impacts of crumb rubber size and concentration on the performance characteristics of porous asphalt mixtures were investigated in this experimental study. Porous asphalt mixtures were modified by dry process using crumb rubber in three different grain size distributions (#4~#20, #20~#200, and #4~#200) and rubber contents of 10%, 15%, and 20% as weight of bitumen. The permeability, Cantabro abrasion, indirect tensile, moisture susceptibility (Modified Lottman), and resilient modulus tests were carried out in this experimental program. Based on the analysis of the results obtained from this study, the following conclusion and recommendation can be drawn.

(i) The optimum bitumen content in the design of porous asphalt was determined to be 6.5%. Although the mix design of porous asphalt mixture has achieved design requirements with penetration grade bitumen of 50/70, the low values in Cantabro abrasion loss and IDT strength tests have demonstrated the necessity of modified bitumen.

(ii) Increasing the crumb rubber size and content significantly reduced the coefficient of permeability. The #20~#200 crumb rubber exhibited better performance than other grain size distributions, and the coefficient of permeability at the 10% rubber content remained over the limit value (100 m/day). The permeability test result showed that the small size of rubber particle reduced air voids and the coefficient of permeability due to its surface area.

(iii) Cantabro abrasion loss of mixtures increased as the content of rubber increased for all rubber particle sizes. The optimum rubber concentration was determined to be 10%. All rubber contents of #20~#200 indicated an improvement of Cantabro abrasion loss compared with other rubber gradation. The maximum particle loss of 130% occurred at 20% content of #4~#20. The larger rubber particle size leads to an increase in the Cantabro abrasion loss on the account of the discontinuity in the bitumen matrix.

(iv) While IDT strength of 12% only improved at 10% content of the #20~#200 crumb rubber, IDT values were significantly reduced for all rubber contents compared to the control specimens. In general, increasing the crumb rubber size decreased the IDT strength of the porous asphalt mixtures. The discontinuity in the matrix formed by large size rubber particle has a negative effect on the cohesion and IDT strength.

(v) The addition of crumb rubber significantly reduced the TSR value except in the case of the 10% content of the #20~#200 crumb rubber. This value was similar to the TSR of control specimens of 58% which remained below limit value of TSR (70%) because of the fact that the control specimens were prepared with unmodified bitumen. Increasing the crumb rubber size has substantially decreased the TSR values. Modified Lottman Test results indicated that the addition of crumb rubber did not improve the moisture susceptibility performance.

(vi) Resilient modulus test results corresponded to the IDT strength and Cantabro abrasion test results. Resilient modulus values were decreased with addition of crumb rubber to the mixtures for all rubber particle sizes. In addition, increasing the crumb rubber size decreased it substantially. The maximum resilient modulus value was obtained in rubber content of 10% at #20~#200. The optimum content of crumb rubber was determined in 10%.

(vii) All test results show that #20~#200 mesh size which includes more spherically formed rubber particles than the other mesh sizes (Figure 4(d)) mixed uniformly in the mixtures and constituted a more rigid bituminous matrix. Therefore, it has partially improved the performance characteristics of porous asphalt mixtures. In contrast, larger rubber particle size leads to the discontinuity in the bitumen film. This larger size affected tensile strength of bitumen film negatively resulting in loss of performance. This effect largely increased the IDT strength of conditioned specimens due to loss of adhesion.

(viii) The larger fiber-like shaped crumb rubber particles improve the indirect tensile strength of dense graded asphalt pavement, but it negatively affects the performance of porous asphalt mixtures depending on less finer aggregate in the porous asphalt mixtures.

It can be recommended that the case of 10% content of the #20~#200 crumb rubber should be used to improve the performance characteristics of porous asphalt mixtures. The rubber content higher than %10 and the size larger than #20~#200 decrease the performance of the mixture significantly. Although the rubber particles size and concentration which was determined in this study by using dry process crumb rubber modification has provided the performance improvement for porous asphalt mixtures, the future investigation can be carried out about fractions of #20~#200 rubber gradation and concentrations less than 10%. Moreover, the wet process which requires additional cost in application should be studied to improve the performance of porous asphalt mixture.

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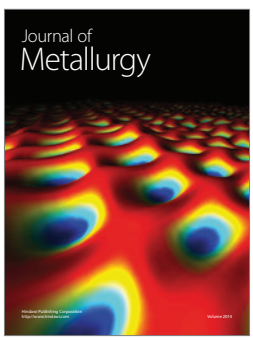




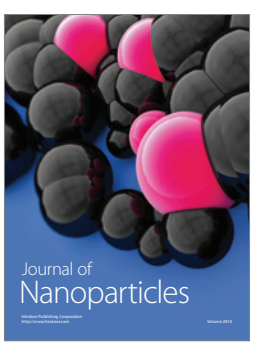


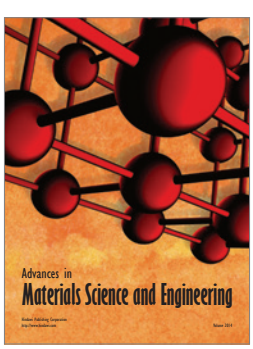


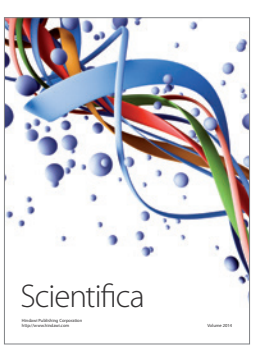


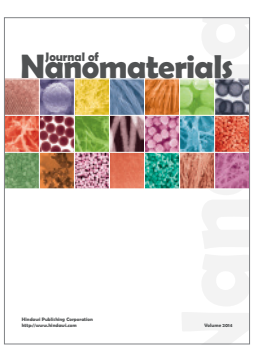






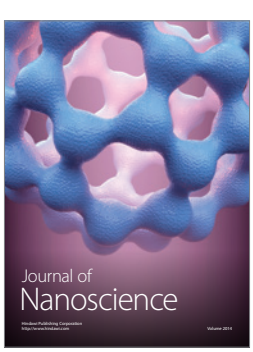




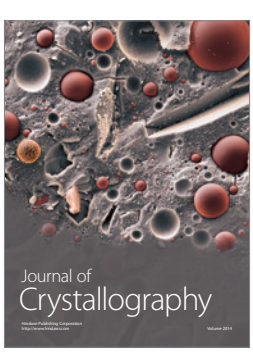




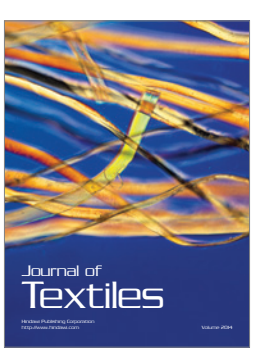












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