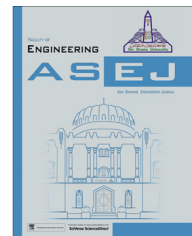




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CIVIL ENGINEERING

Laboratory evaluation of resistance to moisture damage in asphalt mixtures

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Received 12 May 2012; revised 12 October 2012; accepted 24 October 2012

Available online 21 December 2012

KEYWORDS

Moisture damage;
Stripping;
Hydrated lime;
Portland cement;
Flexible pavement;
Asphalt mixtures

Abstract Moisture damage in asphalt mixtures refers to loss in strength and durability due to the presence of water. Egypt road network is showing severe deterioration such as raveling and stripping because the bond between aggregates and asphalt film is broken due to water intrusion. To minimize moisture damage, asphalt mixes are investigated to evaluate the effect of air voids, degree of saturation, media of attack and the conditioning period. Two medias of attack are considered and two anti-stripping additives are used (hydrated lime and Portland cement). The retained Marshall stability and tensile strength ratio are calculated to determine the resistance to moisture damage. The results showed that both lime and cement could increase Marshall stability, resilient modulus, tensile strength and resistance to moisture damage of mixtures especially at higher condition periods. Use of hydrated lime had better results than Portland cement.

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1. Introduction

Environmental factors such as temperature, air, and water can have a profound effect on the durability of asphalt concrete mixtures. In mild climatic conditions where good-quality aggregates

and asphalt cement are available, the major contribution to the deterioration may be traffic loading, and the resultant distress manifests as fatigue cracking, rutting (permanent deformation), and raveling. However, when a severe climate is in question, these stresses increase with poor materials, under inadequate control, with traffic as well as with water which are key elements in the degradation of asphalt concrete pavements. Water causes loss of adhesion at the bitumen–aggregate interface. This premature failure of adhesion is commonly referred to as stripping in asphalt concrete pavements. The strength is impaired since the mixture ceases to act as a coherent structural unit. Loss of adhesion renders cohesive resistance of the interstitial bitumen body useless. Water may enter the interface through diffusion across bitumen films and access directly in partially coated aggregate. Water can cause stripping in five different mechanisms such as detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour [1].

Abbreviations: MS, marshall stability; Vair, air voids ratio; TW, tap water; SW, sea water; QM, marshall quotient; RMS, retained marshall stability; d, day; Mr, resilience modulus; ITS, indirect tensile strength; TSR, tensile strength ratio; NT, non-treatment; CT, cement treatment; LT, lime treatment; CP, condition period; HMA, hot mix asphalt.

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Peer review under responsibility of Ain Shams University.



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Many variables affect the amount of moisture damage which occurs in an asphalt concrete mixture. Some of these variables are related to the materials forming hot mix asphalt (HMA) such as aggregate and bitumen. Others are related to mixture design and construction (air void level, film thickness, permeability, and drainage), environmental factors (temperature, pavement age, freeze-thaw cycles, and presence of ions in the water), traffic conditions and type, and properties of the additives. To alleviate or to control the deformations due to water damage, various researches were performed leading to the utilization of anti-stripping additives. Anti-stripping additives are used to increase physico-chemical bond between the bitumen and aggregate and to improve wetting by lowering the surface tension of the bitumen. The additives that are used in practice or tested in the laboratory include: (i) traditional liquid additives, (ii) metal ion surfactants, (iii) hydrated lime and Portland cement, (iv) silane coupling agents, and (v) silicone [2].

The previous laboratory and field testing have proved that hydrated lime not only improves the composition rather produces multifunctional benefits in the mixtures. It substantially improves low temperature fracture toughness without reducing the ability to dissipate energy through relaxation. Further, hydrated lime acts as filler and reacts with bitumen resulting in some of the beneficial mechanisms, in terms of strength. It has been widely observed that there are also benefits of the reduced susceptibility to age hardening and the improved moisture resistance [3].

2. Problem statement and study objective

Maintenance of roads in Egypt costs annually high percentage of the total road construction costs or in other words, in the futures, the maintenance cost will have equaled the construction cost of new roads. Roads in Egypt usually show excessive failures of an early stage of pavement life. Some factors contributing to the early failures are excessively high temperature and humidity. On highways and urban roads, damaged spots can be seen after the seasonal rains, which may cause stripping due to the properties of local aggregates. Moreover, the severe water damage problems in Egypt are due to the high water table. The rising of the water table is accelerated due to its huge coastal locations on red and white seas as well as on the River Nile. Therefore, the road network is facing a lot of durability problems including stripping, raveling and pothole formation.

The pavements in Egypt are usually attacked by two types of water, including sea water (SW), and tap water (TW). In the laboratory, conditions are simulated to evaluate the effect of saturation degree (S_r), air voids (V_{air}) and medium of attack on indirect tensile strength (ITS) and the resilience modulus (M_r). This will give a quantitative measure of durability conditions of AC mixtures used in Egypt. Moreover, this will help to predict moisture damage in the areas suffering from water damage problems. The specific objectives of this research were:

- (1) To evaluate the moisture damage characterization of hot-mix asphalt mixtures based on laboratory evaluation and study its effect on the asphalt mechanical properties such as resilience modulus, stability and tensile strength.

- (2) To evaluate the effect of different treatments such as lime and cement for controlling the stripping and reducing moisture damage compared to the untreated mixtures.
- (3) To come up with recommendations to minimize the effect of moisture on pavement performance in Egypt.

3. Factors affecting moisture susceptibility of asphalt pavement

Moisture damage in asphalt concrete pavement is affected by many factors [4]:

- (a) The type of aggregate, both coarse and fine, must be examined carefully in evaluating the water damage of the mixture. Some aggregates such as granite, gravel and other siliceous type materials are sensitive to moisture and are prone to stripping when incorporated in asphalt concrete. Other aggregates such as limestone are less susceptible to moisture damage. In some cases, the majority of the stripping takes place in the coarse aggregate portion of the mixture. In some cases, the fine aggregate is more moisture sensitive and most stripping occurs in that part of the mixture.
- (b) The second factor is the type of source of crude oil and refining process which is used to manufacture the asphalt cement. Most asphalt cements are relatively inert in regard to moisture damage. The asphalt cements, from one to another; do not show much difference in the degree of stripping. In other words, the source of asphalt cement is much less dominant than the type of aggregate.
- (c) The third factor is the asphalt concrete mixture properties. The air void level and the permeability of the mixture, which are influenced by the degree of compaction, asphalt cement and the aggregate gradation, are important since they control the level of water saturation and drainage. At high air void contents, above 6%, a given mixture can suffer a considerable degree of moisture damage. Exception is made for open graded mixtures where air void levels of 15–25% allow water to drain.
- (d) The asphalt film thickness has also an influence on the moisture susceptibility characteristics of HMA because it affects durability of the mixture. Thick films which are associated with black flexible mixtures are known to be durable. On the other hand, thin films which are associated with brownish, brittle mixtures tend to crack and ravel excessively thus shortening the service life of the pavement. Mixtures with thick asphalt film are less susceptible to water damage than the mixtures with thin asphalt film since very little quantities of water can move through the mixture that contains thick asphalt film thicknesses.
- (e) Environmental conditions and traffic affect the amount of stripping which happens in a particular mixture. More moisture damage typically occurs in areas where there are considerable amount of rain and/or snowfall. Both the type of traffic and the volume are important variables. As the traffic becomes heavier and as the truck volume increases, the amount of stripping becomes greater.

4. Literature review

4.1. Causes of moisture damage

Moisture damage can be defined as the loss of strength and durability in asphalt mixtures due to the effects of moisture. Moisture can damage HMA in two ways: (1) loss of bond between asphalt cement or mastic and fine and coarse aggregate or (2) weakening of mastic due to the presence of moisture. There are six contributing factors that have been attributed to causing moisture damage in HMA: detachment, displacement, spontaneous emulsification, pore-pressure-induced damage, hydraulic scour, and environmental effects. Not one of the above factors necessarily works alone in damaging an HMA pavement, as they can work in a combination of the processes. Therefore, a need exists to examine the adhesive interface between aggregates and asphalt and the cohesive strength and durability of mastics (Graff, 1986; Roberts et al. 1996; Little and Jones, 2003; Cheng et al. 2003) [5]. A loss of the adhesive bond between aggregate and asphalt can lead to stripping and raveling, while a loss of cohesion can lead to a weakened pavement that is susceptible to premature cracking and pore pressure damage (Majidzadeh and Brovold, 1968; Kandhal, 1994; Birgisson et al., 2003). Yet almost all of studies aimed at a comparative measure of moisture damage, either via visual observations from field data or laboratory tests or via wet-versus-dry mechanical tests to give a so called moisture damage index parameter [6].

Lu and Harvey [7] evaluated the resistance to moisture damage of an HMA mix manufactured with a California aggregate that is known to have poor compatibility with asphalt binder. They used fatigue and tensile strength tests to evaluate the resistance to moisture damage of mixes. The tensile strength properties of the evaluated mixture showed that hydrated lime improves the tensile values at both un-conditioned and moisture-conditioned stages. They show that the tensile ratios of the lime-treated mixture are significantly higher than the control and liquid treated mixtures. In addition, fatigue properties indicated that the lime-treated mixture started with higher fatigue life than the control and the two liquid-treated mixtures, and maintained higher fatigue life after moisture damage.

4.2. Determining moisture susceptibility

The presence of water in an asphalt pavement is unavoidable. Several sources can lead to the presence of water in the pavement. Water can infiltrate the pavement from the surface via cracks in the surface of the pavement, via the interconnectivity of the air-void system or cracks, from the bottom due to an increase in the ground water level, or from the sides. Inadequate drying of aggregate during the mixing process can lead to the presence of water in the pavement as well [6]. Asphalt concrete mixes used in Jeddah city road network were investigated by Abdul Wahhab and Hasnain [8]. Three media of attack were considered: fresh water, sea water and soap-diluted water. A number of treatments were carried out on asphalt mixes, including filler replacement by Portland cement, aggregate coating by Portland cement, addition of lilamine as an anti-stripping agent and use of emulsified asphalt instead of asphalt cement. Results indicated that modulus of resilience, indirect tensile strength and fatigue life decreased with

increase in degree of saturation. Highest strength parameters were obtained for fresh water and lowest in the case of soapy water. Portland cement coating and replacement of filler by Portland cement were found to be effective in reducing stripping.

In order to combat this stripping, proper mix design is essential. However, if a mix is properly designed but not compacted correctly, it may still be susceptible to moisture damage because of high air void content that permits water to enter the HMA pavement. Therefore, a HMA should be tested in a situation where moisture does infiltrate the air voids of the mixture. Many tests were performed at 7% air voids for this reason. The final step in the Superior Performing Asphalt Pavement System (SUPERPAVE) was evaluation of moisture susceptibility of the HMA mix. AASHTO T-283 was used in this testing where tensile strength ratio (TSR) value less than 70% was considered moisture susceptible [9].

Feipeng et al. [10] investigated the moisture susceptibility of the HMA mixtures containing moist aggregates. The experimental results indicated that the mixtures with moist aggregate generally had lower wet ITS values than mixtures without moisture. In addition, TSR values of mixtures were generally greater than 85% regardless of moisture content. Kanitpong and Bahia [11] evaluated the relationship between the performance of asphalt pavements (pavement distress index PDI) in the field and the (TSR) values measured in laboratory. The results indicated that there was no relationship between the TSR values and the field pavement performance as measured by the PDI. In addition, the data could not be used to find a relationship between the TSR and specific pavement distresses that are known to be related to the moisture damage (such as surface raveling and rutting). Moreover, aggregate mineralogy did not show a relationship to the pavement performance. The pavement performance could be affected by other factors such as the production and construction of the mixture, asphalt binder used, and aggregate gradation. Further, there was an effect of using anti-stripping additives on the pavement performance (as measured by the PDI) and also an effect on the specific pavement distresses. Pavements with mixtures containing anti-stripping additives show less increase in rutting and, on average better performance based on PDI values. It also appeared that the TSR testing could only show the effect of anti-stripping additives but did not correlate to performance. There could be other tests that were simpler and could effectively indicate the existence of anti-stripping additive or an improved level of adhesion. Improved level of adhesion was hypothesized to be the cause of improved performance.

The relationship between hot mix asphalt moisture damage, air void structure, pore pressure, and cohesive and adhesive bond energies was investigated by Castelblanco et al. [12]. The air void distribution was found to significantly influence moisture damage. Tensile strength ratios that pass for a mix at 6% air voids and 55% saturation may fail at a higher level of air voids and degree of saturation even though both levels are within AASHTO T-283 specifications. This suggests tightening of the specification range for air voids and degree of saturation. Mohamed et al. [13] investigated many factors associated with construction, which can influence the stripping susceptibility of compacted asphalt concrete pavements. Cores recovered from field-compacted pavements were used throughout the investigation. The results of the experimental investigation

indicated that construction had a significant influence on the compacted mix resistance to stripping. The study also identified surface water as the water source and construction cracks as the route for surface water to the pores inside the mix. Vacuum saturation, used as part of the moisture conditioning procedure, had in the past obscured the influence of construction-induced cracks on stripping susceptibility.

4.3. Effect of anti-stripping additives

Gorkem and Sengoz [1] aimed to determine the effect of additives such as hydrated lime as well as elastomeric (SBS) and plastomeric (EVA) polymer modified bitumen (PMB) on the stripping potential and moisture susceptibility characteristics of hot mix asphalt (HMA) containing different types of aggregate (basalt–limestone aggregate mixture and limestone aggregate). The results indicated that hydrated lime addition and polymer modification increased the resistance of asphalt mixtures to the detrimental effect of water. Moreover, it was found out that samples prepared with SBS and PMB exhibited more resistance to water damage compared to samples prepared with EVA and PMB.

Jordan and Amirghanian [14] investigated of HMA mixtures which contain moist aggregate. The conventional testing procedures such as indirect tensile strength (ITS), tensile strength ratio (TSR), deformation, and toughness were performed to determine the moisture susceptibility of the mixtures. The experimental design included two percentages of moisture content (0% and ~0.5% by weight of the dry mass of the aggregate) and two WMA additives (Asphamin and Sasobit). The test results indicated that, dry ITS values are affected by the aggregate moisture and hydrated lime contents while the use of HMA additive does not significantly alter the dry ITS and toughness values. Statistical analysis showed that there were no significant differences in the wet ITS values of HMA mixture amongst three types of mixtures (control, Asphamin, and Sasobit) under identical conditions (same moisture and lime contents). In addition, statistical analysis also illustrated that wet ITS values, generally, were statistically different for the mixtures made with various aggregate sources. Furthermore, the deformation resistance of mixtures containing moisture were lower than those made with dry aggregate. However, the results indicated that the addition of hydrated lime increases the deformation resistance of all mixtures.

Generally, Research work in the area of asphalt concrete stripping reflects general agreement among researches that existing adhesion theories do not completely describe the stripping phenomenon. The stripping mechanisms fail to specify the source of water necessary for stripping to start and progress with time. Locating the water source and route to the pavement interior is of great significance to effort seeking a preventive measure against stripping.

4.4. Adhesion theories

Four theories are used to describe the adhesion characteristics between asphalt and aggregate. The four theories are chemical reaction, surface energy, molecular orientation, and mechanical adhesion. Surface tension of asphalt cement and aggregate, chemical composition of asphalt and aggregate, asphalt viscosity, surface texture of aggregates, aggregate porosity, aggregate clay/silt content, aggregate moisture content, and temperature

at the time of mixing with asphalt cement and aggregate are material properties that affect adhesion [5]. According to Al-Swailmi and Terrel [15], the adhesion test of asphalt binder was conducted by using the Pneumatic Adhesion Tensile Testing Instrument (PATTI). The Pull-Off tensile strength test of asphalt binders with and without anti-stripping additive was conducted. According to results, it is obviously seen that the use of anti-stripping additive results in higher pull-off strength for all aggregate samples. As a result, it is believed that the anti-stripping additive can improve the adhesion property of the bond between asphalt binder and aggregate surface especially for the bond under the water exposed condition. Cheng et al. [16] reported that the adhesion failure model was developed to analyze the adhesive fracture between asphalt and aggregate in the presence of water. Cohesive and adhesive fractures in an asphalt–aggregate system are directly related to the surface energy characteristics of asphalt and aggregate. The surface energy of adhesion with or without the presence of water can be calculated from the surface energies of asphalt and aggregate.

4.5. Cohesion theories

Cohesion is developed in a mastic and is influenced by the rheology of the filled binder. The cohesive strength of a mastic is a function of the interaction between the asphalt cement and mineral filler, not just of the individual components alone. The cohesive strength of a mastic is weakened due to the presence of water through increased saturation and void swelling or expansion [5]. Cheng et al. showed that the cohesive strength can be damaged in various mixtures by the diffusion of water into asphalt mastics [16]. According to Khosla and Birdsall [17], the triaxial test also provides a method of determining the cohesion (C) and friction angle (ϕ) of the material which can be represented on a Mohr diagram. The cohesion value is affected by the aggregate–asphalt bonding of the mixture, and the friction angle is related to the internal friction of the mix. Based on these definitions, moisture should only affect the cohesion of the mixture and not the friction angle. The data shows that the proposed test provides a method of measuring cohesion and friction angle of a mixture. These two fundamental material properties are a viable means of assessing a mixture's moisture sensitivity. Having a constant value suggests that only the adhesion of the mix, which is the bonding of aggregate and asphalt, is affected by the moisture. The loss in cohesion of a mix when conditioned may be used to determine if the addition of an additive is required. If an additive is utilized the proposed test is capable of evaluating the effectiveness of the additive in improving the cohesion of the mixture.

5. Research approach

Moisture damage in asphalt mixtures refers to loss in strength and durability due to the presence of water. The level and the extent of moisture damage, also called moisture susceptibility, depend on environmental, construction, and pavement design factors; internal structure distribution and the quality and type of materials used in the asphalt mixture. In order to assess the moisture destruction, the current study bears out an analytical approach based on experimental tests.

To achieve the above stated objectives, the effect of degree of saturation, air voids content and medium of attack on the mechanical properties of asphalt mixtures are studied. Each factor is varied in the following manner.

- (1) Degree of saturation: testing is made at (0.0%, 10%, 25%, 50% and 80%) saturation level. Mixes are evaluated for tensile strength to evaluate the water damage of the specimens.
- (2) Air voids: to evaluate the effect of air void on the moisture damage, the asphalt mixtures are designed for 1.5%, 4% and 6% air voids.
- (3) Medium of attack: samples are immersed in two types of water including tap water (FW) and sea water (SW). All tests are performed to evaluate the effect of these media for different condition periods (1, 3, 7, and 14 days).
- (4) Treatments for asphalt mixtures such as adding Portland cement and hydrated lime are carried out. Marshall samples are fabricated and tested for tensile strength to see the effectiveness of each additive compared to untreated mixtures.

The flow chart of the experimental study and design parameters are presented in Fig. 1.

6. Materials

6.1. Asphalt cement

Asphalt cement (AC 60/70) obtained from a local petroleum refinery is used in this study. Table 1 summarizes the physical properties of this asphalt.

6.2. Aggregates

Crushed limestone aggregate from EL-Suez city obtained by the general Nile company of desert roads is utilized in asphalt mixtures. A crushed stone with angular particles and rough surface texture is used as course aggregate. Natural sand with particles ranging from 0.09 to 2.0 mm is used as fine aggregates. lime stone dust is used as mineral filler. Table 2 summarizes the physical properties of the aggregates, while Table 3 summarizes the gradation of aggregates according to ASTM C136 specification.

6.3. Anti-stripping additives

Hydrated lime as well as Portland cement are used as a filler in asphalt mixtures. The properties of both anti-stripping additives are given in Table 4.

7. Laboratory experimental investigation

7.1. HMA specimens fabrication

The specimens are prepared according to the Asphalt Institute Manual (MS-2). The asphalt cement and limestone aggregate are mixed at 155 °C. Marshall specimens are prepared using the standard Marshall hammer with 35, 50 and 75 blows on each side of cylindrical samples at 5.2% bitumen content. The average of air voids ratio (%Vair) is obtained as 6%,

4% and 1.5% respectively. The conditioned specimens are immersed in tap water (TW) as well as sea water (SW) for different condition periods (1, 3, 7, 14 days).

The specimens are loaded to failure at a constant rate of compression of 1.65 mm/min. The ratio of stability (kN) to flow (mm), stated as the Marshall quotient (MQ), and as an indication of the stiffness of the mixes. It is well recognized that the MQ is a measure of the materials resistance to shear stresses, permanent deformation and hence rutting [18]. High MQ values indicate a high stiffness mix with a greater ability to spread the applied load and resistance to creep deformation. To determine the resistance of mixtures to moisture damage, the retained Marshall stability (RMS) is obtained by using the average stability in the following formula 1 [18]:

$$RMS = 100(MS_{cond}/MS_{uncond}) \quad (1)$$

where RMS is the retained Marshall stability, MS_{cond} is the average Marshall stability for conditioned specimens (kN) and MS_{uncond} is the average Marshall stability for unconditioned specimens (kN). An index of retained stability can be used to measure the moisture susceptibility of the mix being tested.

7.2. Moisture conditioning

The moisture conditioning is used to evaluate the effects of water saturation of compacted bituminous mixtures in the laboratory. The hot-mix asphalt specimens conditioning is performed according to AASHTO T283 by immersing the specimens in water (sea or tap water) and exposing them to a vacuum for different treatment periods to achieve saturation levels up to 80%. As a result, the investigated saturation degree in this study are (0.0%, 10%, 25%, 50% and 80%), by this method the water damage of the specimens becomes more effective.

7.3. Indirect tensile strength

The stripping resistance of asphalt mixtures is evaluated by the decrease in the loss of the indirect tensile strength (ITS) according to AASHTO T283 test procedure. In the indirect tensile strength test, cylindrical specimens are subjected to compressive loads, which act parallel to the vertical diametric plane by using the Marshall loading equipment. This type of loading produces a relatively uniform tensile stress, which acts perpendicular to the applied load plane, and the specimen usually fails by splitting along with the loaded plane [19]. Based upon the maximum load carried by a specimen at failure, the ITS was calculated from the Eq. (2) [18]:

$$ITS = \frac{2000 \times P}{\pi \times h \times D} \quad (2)$$

where ITS is the indirect tensile strength (kPa); P the maximum load (N); h the specimen thickness (mm); and D is the specimen diameter (mm).

Hydrated lime in asphalt mixtures refers to loss in strength and durability due to the presence of water. The level and the extent of moisture damage, also called moisture susceptibility, depend on environmental, construction, and pavement design factors; internal structure distribution and the quality and type of materials used in the asphalt mixture. Moisture susceptibility of the compacted specimens is evaluated by tensile strength ratio (TSR) using Eq. (3) [19]:

Table 3 Gradation of aggregates.

Opening size	Gradation (%)	Specification limits
3/4"	100	100
1/2"	90.5	83–100
3/8"	80.5	70–90
No. 4	47.3	40–55
No. 10	33	25–38
No. 40	13.5	10–20
No. 80	9	6–15
No. 200	5.3	4–10

$$TSR = \frac{S2}{S1} \quad (3)$$

where TSR is the tensile strength ratio. S2 the average indirect tensile strength of conditioned specimens. S1 is the average indirect tensile strength of dry (unconditioned) specimens.

8. Results and discussion

8.1. Marshall stability and flow test

The Marshall stabilities (MSs) and flows for tested specimens are given in Table 5. The values are considered the average of three samples. For both medias of attack, it can be observed that with decreasing the air void ratio, the stability increases and the flow decreases while with decreasing the condition period the stability and the flow increase.

Fig. 2 illustrates the Marshall quotient (MQ) values for both conditioned and unconditioned mixtures. It is well recognized that the MQ is a measure of the material's resistance to shear stresses, permanent deformation and hence rutting. It can be concluded that the resistance to rutting (MQ) for conditioned specimens in sea water are lower than them in tap water at the same period. Further, the air void content (%Vair) in the mixes has a significant effect on the rutting resistance where MQ values decrease by about 50% with increasing Vair from 1.5% to 4%. Moreover, the resistance to rutting decreases with increasing condition period.

The index of retained Marshall stability (RMS) can be used to measure the resistance of mixtures to moisture damage of the mix being tested. As shown in Fig. 3, it can be obtained that the RMS values slightly decrease with increasing air voids and extremely decrease with increasing condition period (CP)

especially for sea water conditioned specimens. The average of RMS reduction values for CP of 3, 7 and 14 days compared with 1 day were 8.1, 46.7 and 56.7 respectively for tap water and 32.3, 59.6 and 68.4 respectively for sea water. It can be assumed that 14 days conditioning in tap water has approximately the same effect of 7 days conditioning in sea water with regard to moisture damage.

8.2. Resilient modulus of asphalt mixtures

In recent years, there has been a change in philosophy in asphalt pavement design from the more empirical approach to the mechanistic approach based on elastic theory. Resilient modulus of asphalt mixtures is the most popular form of stress–strain measurement used to evaluate elastic properties [19]. It is well known that most paving materials are not elastic but experience some permanent deformation after each load application. However, if the load is small compared to strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and proportional to the load and can be considered as elastic [13]. According to Abdul Wahhab and Hasnain [8] the resilience modulus (Mr) can be calculated using the maximum load applied and the horizontal elastic tensile deformation as shown in the following equation:

$$Mr = p \frac{\mu + 0.2732}{h\delta} \quad (4)$$

where Mr is the modulus of resilience (MPa). p the maximum load applied (N); h the sample thickness (mm). δ the recoverable horizontal deformation (mm); μ is the Poisson's ratio (assumed as 0.35).

The previous equation is rewritten by Niazi and Jalili [20] as shown in the following equation:

$$Mr = 1.58(MS/F) \quad (5)$$

where is the Mr is the modulus of resilience (N/mm²); MS the Marshall stability of the specimen (N); F the flow of the specimen (mm).

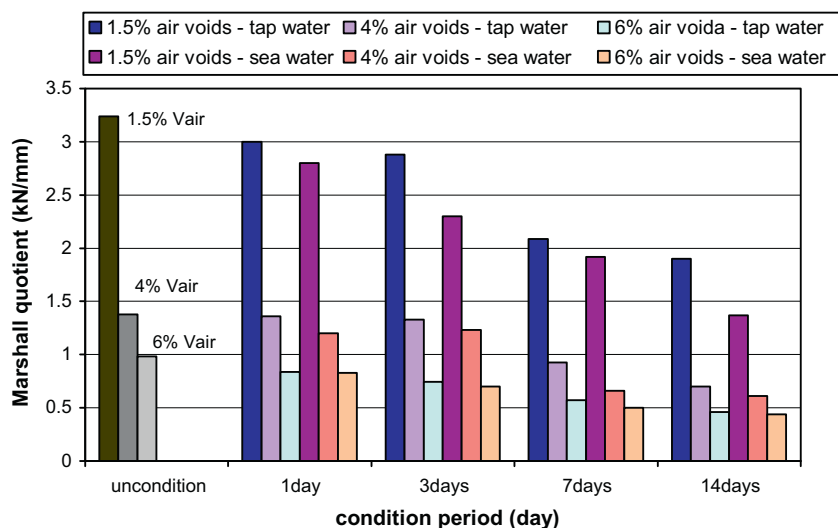
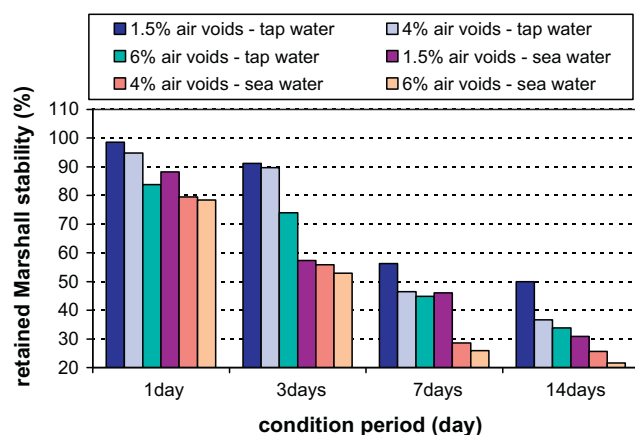
Fig. 4 shows the effect of (CP) and (%Vair) on the resilient modulus of asphalt mixes. It can be concluded that with increasing (CP) and (%Vair) the Mr values decreased. The values of Mr vary with the medium of attack, where the lowest values are obtained in the case of sea water. The modulus values are reduced by about 30% and 40% at, 4% and 6% air

Table 4 Properties of the used Anti-stripping additives.

Portland cement		Hydrated lime	
Properties	Value	Chemical properties	Value
Specific gravity	3.15	Total CaO (%)	85.78
Initial setting time (min)	150	Active Ca(OH) ₂ (%)	82.04
Final setting time (min)	185	MgO (%)	3.52
Volume expansion (mm)	2.0	Loss in ignition (%)	22.51
Compressive strength (MPa)		SO ₃ (%)	1.47
2 days	22.0	CO ₂ (%)	3.89
7 days	38.7	R ₂ O ₃ (%)	1.41
28 days	46.8	Physical properties	Value
		Sandy-over 90 µm	6
		Density (kg/m ³)	472

Table 5 Mixtures properties for Marshall test.

Media of attack			Media of attack								Unconditioned specimens
			Tap water (TW)				Sea water (SW)				
Condition period			1	3	7	14	1	3	7	14	
Air voids ratio (%Vair)	1.5%	MS (KN)	6.7	6.2	3.83	3.4	6.0	3.9	3.13	2.1	6.8
		Flow (mm)	2.2	2.15	1.835	1.78	2.1	1.7	1.63	1.53	2.1
	4%	MS (KN)	3.7	3.5	1.812	1.43	3.1	2.18	1.116	1.0	3.9
		Flow (mm)	2.71	2.62	2.49	2.05	2.55	1.77	1.675	1.62	2.82
	6%	MS (KN)	3.1	2.74	1.66	1.25	2.90	1.96	0.96	0.8	3.7
		Flow (mm)	3.7	3.675	2.9	2.69	3.5	2.8	1.94	1.8	3.76

**Figure 2** MQ values for conditioned and unconditioned mixtures.**Figure 3** Effect of condition period on RSM values.

voids respectively. These results are similar to those obtained by Epps et al. [21].

8.3. Indirect tensile strength (ITS)

The stripping resistance of asphalt mixtures is evaluated by the decrease in the loss of the indirect tensile strength (ITS). From Fig. 5 the ITS values decrease with increasing both of air voids

and condition period. The stripping resistance are reduced by about 22% and 30% at 4% and 6% air voids respectively. On another hand, lower stripping resistance are observed in the case of sea water conditioning especially at 6% air voids. The average reduction ratios of tensile strength (RVts) is indicated to the loss of indirect tensile strength of sea water conditioned mixtures compared with tap water conditioned mixtures. As shown in Fig. 6, It can be observed that (RVts) values increase with increasing both of condition period and air voids.

The effect of air voids on the average lateral displacement (ΔL) obtained through the indirect tensile test is shown in Fig. 7. It can be concluded that with increasing the condition period, the lateral displacement decreases. Further, for conditioned specimens the maximum (ΔL) is achieved at 4% air voids where after 3 days condition period the effect of air voids can be neglected. For medias of attack, sea water obtains lower lateral displacement than tap water conditioning while the unconditioned specimens have the highest ΔL values.

Tensile strength ratio (TSR) is used to predict the moisture susceptibility of the mixtures. According to previous researches a TSR of 0.8 or above has typically been utilized as a minimum acceptable value for hot mix asphalt. Mixtures with tensile strength ratios less than 0.8 are moisture susceptible and mixtures with ratios greater than 0.8 are relatively resistant to moisture damage [20]. Fig. 8 illustrates tensile strength ratio for both tap and sea water conditioning. It is

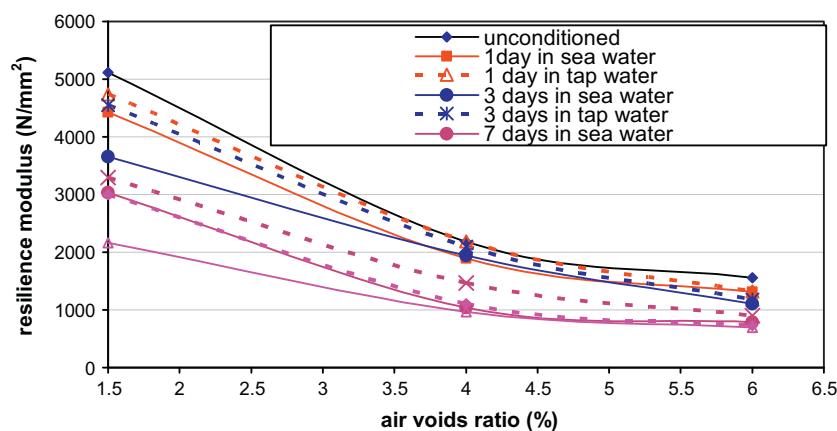


Figure 4 Effect of air voids ratio on Mr.

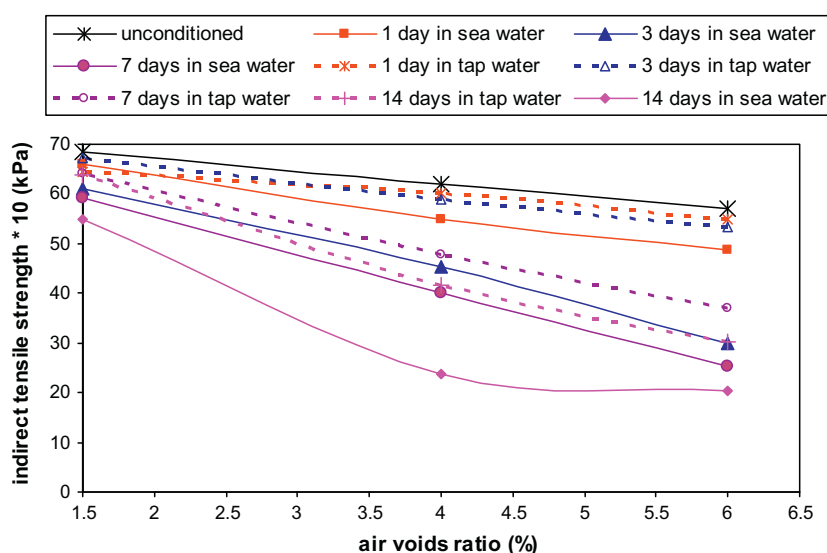


Figure 5 Effect of air voids on the tensile strength.

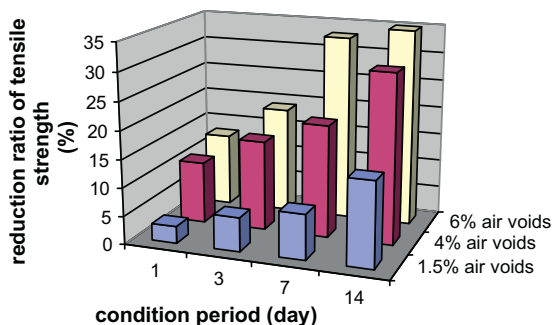


Figure 6 Average reduction ratios of tensile strength.

seen that the TSR values decrease as the condition period (CP) increases, the rate of decreasing becomes more obvious at higher air voids. In the following cases the mixtures are considered resistant to moisture damage:

- (1) all mixtures with 1.5% air voids,
- (2) at condition period of 1 day for both conditioning types,
- (3) at conditioning period of 3 days for tap water.

Excluding these cases, the remaining mixtures are moisture susceptible. It is clear that the mixtures conditioned in sea water show lower TSR compared with tap water.

8.4. Effect of saturation degree on tensile strength

Marshall specimens are prepared by using the standard Marshall hammer with 50 blows on each side before conditioning them in the vacuum saturation soaking apparatus. Different ratios of the air voids are filled with water hence, the water damage of the specimens becomes more effective. Specimens showing above 80% saturation after the vacuum soaking are discharged since they are accepted as severely saturated. From Fig. 9 it can be illustrated that the stripping resistance reduces by about 19–40% with increasing the degree of saturation from 50% to 80% respectively.

9. Effect of hydrated lime and Portland cement treatment

Hydrated lime and Portland cement are commonly used as a solid type anti-stripping agents [15–18]. When these additives

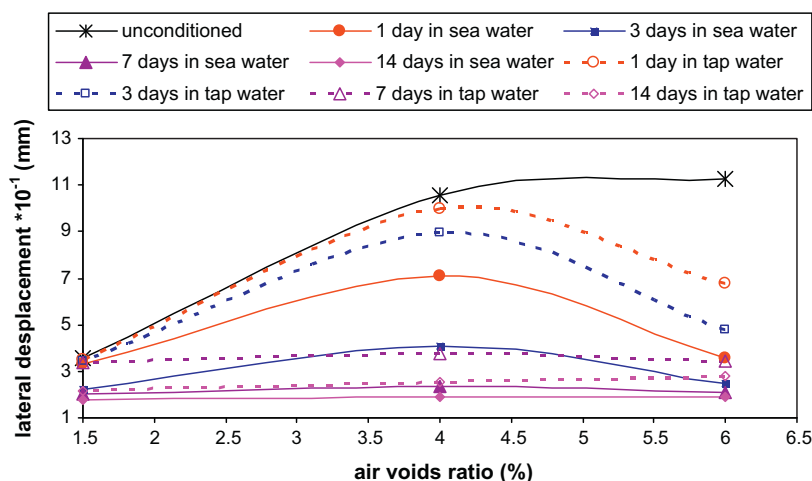


Figure 7 Effect of air voids on the lateral displacement.

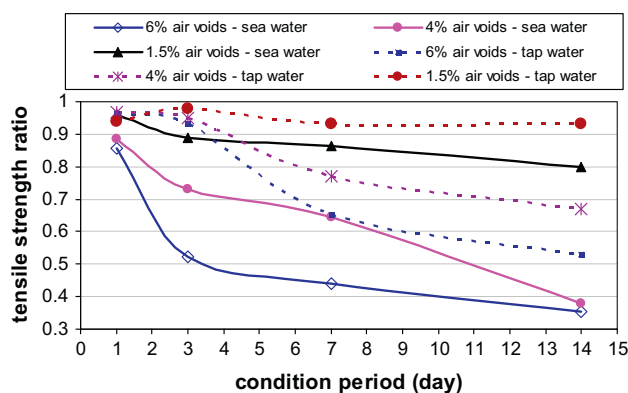


Figure 8 Effect of condition period on TSR.

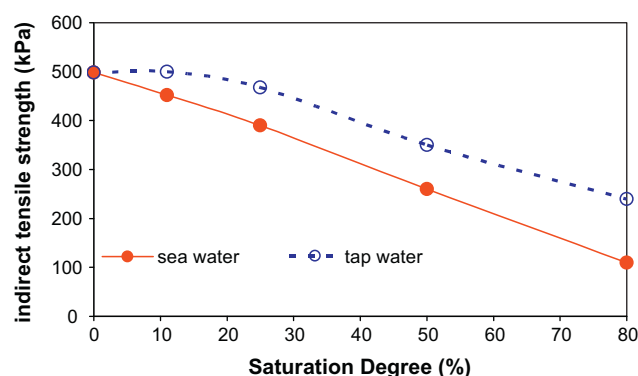


Figure 9 Effect of saturation degree on ITS.

are added to HMA, they react with aggregate and strengthen the bond between the bitumen and the aggregate interface. Anti-stripping agents react with highly polar molecules to inhibit the formation of water-soluble soaps that promote stripping. When those molecules react with anti-stripping agents, they form insoluble salts that no longer attract water [20]. Thus, hydrated lime as well as Portland cement can reduce pavement damage because of their distinct stiffening effects and reduce moisture-associated damage by improving the aggregate-asphalt bonding [1–3,8,14]. This part of the paper aims to compare between the Portland cement and the hydrated lime in improving the resistance of asphalt mixtures to rutting (MQ), the resistance to moisture damage (RMS), the stripping resistance (ITS) and the moisture susceptibility of asphalt mixes (TSR). According to many studies [1,3,10], these additives are added by 1.5% of the total aggregate weight as mineral filler.

9.1. Marshall results

Marshall specimens are prepared by using the standard Marshall hammer with 50 blows. Figs. 10 and 11 illustrate the values of Marshall quotient (MQ) and the retained Marshall stability (RMS) for untreated (NT), cement treated (CT) and lime treated (LT) specimens. From Fig. 10, it is seen that the

treated specimens with lime give the highest rutting resistance (MQ) for both medias of attack (sea and tap water). The lime treatment increases the rutting resistance by about 30% and 100% more than each cement and untreated specimens respectively. It is assumed that lime stiffens the specimens and prevents high flow so that provides high MQ. The importance of lime addition appears through that the lime treatment provides approximately the same rutting resistance of untreated and unconditioned specimens after 14 days conditioning in sea water or tap water. While the cement treatment provides the same values after only 7 days conditioning period.

From Fig. 11, it is observed that the treated specimens with lime give the highest moisture damage resistance (RMS). Moreover, the moisture damage resistance for untreated mixtures decreases obviously with increasing the condition period while for lime treated mixtures the moisture damage resistance slightly decreases. This result shows the effect of hydrated lime in reducing the moisture susceptibility and so moisture damages of the mix especially at higher condition periods. Lime treated mixtures exhibit significant RMS values between 85% and 61% for condition period up to 14 days. While, cement treated mixtures obtain significant RMS values between 63% and 33% where the untreated mixtures obtain RMS values between 54% and 14%. Further, it can be concluded that the addition of lime after 14 days conditioning in sea water or

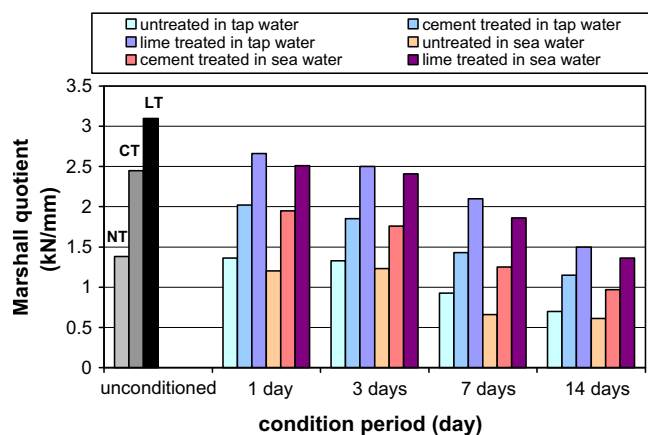


Figure 10 Effect of lime and cement on MQ values.

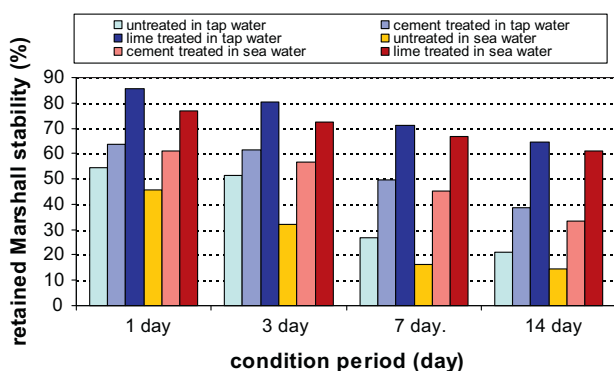


Figure 11 Effect of lime and cement on RMS values.

tap water has approximately same effect of cement addition after 1 day conditioning period with regard to moisture damage. In the same manner, addition of cement after 7 days has same moisture damage resistance of untreated specimens.

9.2. Tensile strength results

The indirect tensile strength test is used to determine the tensile properties of the asphalt concrete which can be further related to the cracking properties of the pavement. Fig. 12 illustrates the average indirect tensile strength (ITS) for asphalt specimens treated with each anti-stripping agents. The result indicates that the use of Portland cement and hydrated lime result in significant increase in tensile strength for both medias of attack. This indicates that the mixture containing additives show higher values of tensile strength at failure indirect tensile strength under static loading this would further imply that modified mixtures appear to be capable of withstanding larger tensile stress prior to cracking. The results also indicates that the use of cement does not seriously increase the tensile strength of the mixtures compared with lime usage especially at higher condition periods.

Fig. 13 illustrates tensile the strength ratio (TSR) for both anti-stripping additives used in this study. The results show that hydrated lime and Portland cement can improve resistance to moisture susceptible of asphalt mixtures especially

at higher condition periods. This implies that introducing cement and lime to the mixtures reduce moisture susceptibility because they are effective adhesive agents for emulsion mixtures [20]. Without these additives the mixtures have poor resistance to water damage. In the case of tap water, the use of lime for conditioning period up to 14 days or cement for period up to 7 days results in significantly higher TSR (above 0.8). In the case of sea water, the use of lime for conditioning period up to 7 days or cement for period up to 3 days are also considered resistant to moisture damage (TSR above 0.8). The samples without additives are moisture susceptible (TSR below 0.8).

10. Conclusions

Many highways in Egypt have been exposing to premature failures that decrease the performance and service life of pavements. One of the major causes of premature pavement failure is the moisture damage of the asphalt concrete layer. The objectives of this study were to evaluate the different variables affecting the amount of water damage in the asphalt concrete layer. Based on the laboratory test results, the following conclusions were drawn:

- (1) Conditioning asphalt specimens in sea water obtained lower Marshall stability, lower flow, lower Marshall quotient MQ, lower modulus of resilience M_r , lower stripping resistance ITS, lower lateral displacement, lower tensile strength ratio TSR and lower retained Marshall stability RMS where 7 days conditioning in sea water had approximately the same effect with 14 days conditioning in tap water with regard to moisture damage. This reduction increased with increasing both of condition period and air voids.
- (2) In the Marshall stability test, Marshall stability values increased and the flow decreased with decreasing the air void ratio. Where increasing the air void from 1.5% to 4% decreased the mixtures rutting resistance MQ by about 50%. According to retained Marshall stability, the moisture damage resistance slightly decreased with increasing air voids and extremely decreased with increasing condition period. Moreover, The resilient modulus values were reduced by about 30% and 40% at, 4% and 6% air voids respectively
- (3) In the indirect tensile strength test, the ITS values decreased with increasing both of air voids and degree of saturation. The stripping resistance reduced by about 19% to 40% with increasing the degree of saturation from 50% to 80% respectively. Further, the maximum lateral displacement was achieved at 4% air voids where the effect of air voids can be neglected after 3 days condition period.
- (4) The addition of hydrated lime increased the MQ by about 30% and 100% more than each cement and untreated specimens respectively where provided after 14 days conditioning approximately the same rutting resistance of untreated and unconditioned specimens. Moreover, Lime treated mixtures exhibited significant retained Marshall stability RMS values ranged between 85% and 61% for condition period up to 14 days.

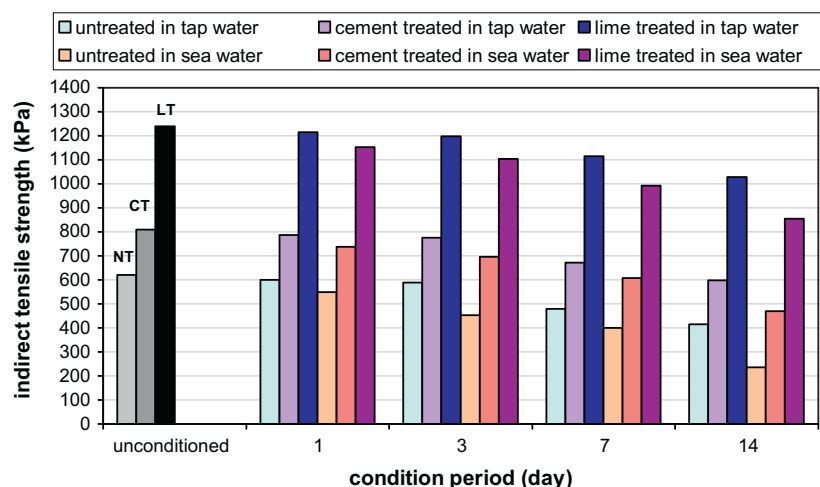


Figure 12 Effect of lime and cement on ITS values.

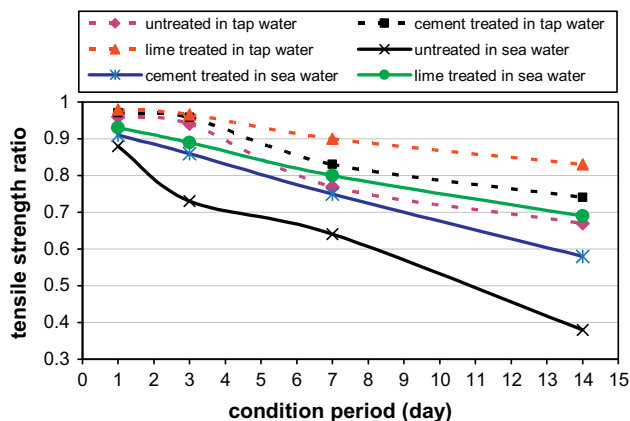


Figure 13 Effect of lime and cement on TSR values.

- (5) The mixture containing additives showed higher indirect tensile strength under static loading this would further imply that treated mixtures appeared to be capable of withstanding larger tensile stress prior to cracking. The use of cement did not seriously increase the tensile strength compared with lime usage.

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