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RESEARCH ARTICLE

INVESTIGATION OF PIEZOELECTRIC RESPONSE IN KAOLIN AND HYDRATED LIME MODIFIED BITUMEN ASPHALT

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ABSTRACT

In this work, the piezoelectric response of modified asphalt design that can significantly solve damage that arises from overloading and high traffic load effects during the service-life were studied. The piezoelectric response of standard and modified binder with 0%, 5%, 10% and 15% of kaolin and hydrated lime content have been studied using voltmeter and Marshall compressive test machine. The results showed that the addition of kaolin and hydrated lime induces the piezoelectric response compared to the standard asphalt mixture. Various types of loadings have been considered throughout this study. It was determined that the type of modifier and applied load have an effect on the result of piezoelectric response on the surface and within an asphalt pavement structure. Also the result showed that modification of bitumen by kaolin and hydrated lime enhances its performance characteristics as well as significantly alters its rheological properties. The rheological studies on kaolin and hydrated lime modified bitumen were made through penetration test. It was observed that kaolin and hydrated lime showed an effect on penetration. Better results were obtained when hydrated lime concentration was at 15%. The mechanical properties of the standard asphalt mixture and modified asphalt mixture with kaolin and hydrated lime were evaluated using Marshall immersion test. This study showed that the effect of kaolin and hydrated lime modifiers with 5%,10% and 15% of modifier satisfy the minimum Ethiopia road authority acceptance criteria of air voids(except at 5%,10% hydrated lime and kaolin content respectively), void mineral aggregate, void filled with asphalt and Marshall stability butflow value do not meet Ethiopia RoadAuthority acceptance criteria.

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INTRODUCTION

In Ethiopia, the majority of the people live in rural areas, and they are farmers. Especially nowadays agricultural products and expansion of urbanization are increasing. So, infrastructures such as long-serving pavements and energy supplies play important role in improving the standard life of those people and also to transport these products from place to place. So, currently asphalt pavements are a crucial part of our nation's strategy for building a high performance transportation network (Abrham, 2010). A well-developed infrastructure is one of the most valuable assets to any nation. Developing and maintaining adequate transportation infrastructures are critical to achieving and sustaining an acceptable standard of living and economic development for a country. The cost of constructing new and maintaining existing pavements are too high those both federal and regional agencies have directed significant investment on infrastructures. However, such costly projects are often failed to provide the required service-life owing to various reasons. Among them, overloading, higher than the planned traffic flow and severe environmental conditions are the most dominant causes of these failures. Cognizant of the negative impact of these problems on the thriving national economy, both the federal and regional governments established road transport security and safety regulatory bodies. In the technological aspect, failure resistant innovative pavement designs and analyzing the mechanism of failures have significant importance for obtaining prolonged service-life pavement asphalts (Anderson, 2006). Regarding the technological aspect, today with the ability to manipulate materials at nanoscale, mankind is eyeing at nanotechnology for bringing solutions to most if not all problems humanity has been facing so far. Infrastructures, as the most critical parameters for assessing the life standards of human, have already benefited from this breakthrough. Today, from sky scrapers to thermally insulate home, from intelligent pavements to efficient hybrid vehicles

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are re-innovated for high performance as well as in environmental friendly ways. The promising future that nanotechnology holds for the transportation infrastructure industry lies in the fact that the design, modification and material characterization at the nano-level translate into better performance properties at the macroscale level. This interesting technology is being adopted by the asphalt pavement infrastructure industry.

In this work, to investigate the properties of modified bitumen binder for the piezoelectric response. Some materials have the ability to alter their electrical properties or state when subjected to mechanical stress. This is called piezoelectric effect. This stress can be caused by hitting or twisting just enough to deform its regular structure without fracturing it. Once the piezoelectric signal is effectively obtained, it can be made technology feasible to measure the axle weight, thereby enabling to remotely regulate vehicles' overloaded axles. By doing so, we can significantly reduce one of the most causative of failures to asphalt pavement performances.

Statement of the Problem

As highlighted in the above section, overloading and high traffic load are the major causes for significant reductions of asphalt roads service-life. As the huge damages from these factors on the national economy and human life are known long before, The Ethiopia government has taken numerous measures through time. Among them to control axle weights and establishing regulatory bodies for security and safety of pavement roads. However, with high cost for installing weighbridges, an instrument that measures the axle weights of trucks, in a country more than 20000 Km of pavements roads so far only nine weighbridges are installed. Moreover, due to lack of awareness and responsibilities of the personnels' assigned on these stations do not take necessary actions on trespassing vehicles. The cumulative effect of all those factors result in early failure of asphalt roads. This work on the piezoelectric response can significantly contribute in resolving overloading problems by constructing self-sensing asphalt roads.

Objective

The main objective of this work is to investigate the piezoelectric response of hydrated lime and kaolin modified bitumen Asphalt.

- To prepare modified bitumen binder via kaolin and hydrated lime nanoadditves;
- To measure voltage change on standard and modified bitumen asphalt;
- To make comparative test on voltage change via hydrated lime and kaolin nanoadditives;
- Determining the optimum modified bitumen content in enhanced asphalt mix design compatible with highest mechanical properties gain;
- Determining the penetration grade of the modified bitumen binders;
- Determining the stiffness of compacted specimen;
- To make comparative test on asphalts made up of the standard or control and modified bitumen with additive of hydrated lime and kaolin.

Scope of the study

This work focused on the effect of hydrated lime and kaolin additive on the mechanical properties such as penetration (hardness or softness), stiffness and stability (strength) testing of specimen of the control and modified bitumen binder. Further, focused on the investigation of piezoelectric response on the additive of hydrated lime and kaolin modified bitumen binder. However, the piezoelectric response couldn't measure directly because of lack of piezoelectric response measuring instrument. Hence the response was determined indirectly by measuring the voltage change against the applied stress; in this case measurement uncertainty was higher.

Significance of the study

The major factor that affects asphalt shelf life is overloading. Given this problem, if there are piezoelectric responses in the modified asphalt, it would be possible to design intelligent asphalt that can sense overweighed/overloaded vehicles and report/inform to the remotely located regulatory bodies thereby enabling to achieving its projected service life. Moreover to recommend for further study.

Limitation

To assess the overall change in piezoelectric response may be difficult due to limitations on technological capabilities. To test the piezoelectric effect that contains additive of kaolin and hydrated lime of modified bitumen binder needs piezoelectric sensor (measuring devices).

Research Methods and Materials

Research methodology

This study involved investigating the piezoelectric response and rheological properties of bituminous mixture with kaolin and hydrated lime additives prepared in the laboratory. The materials used in the mixture includes: Angular aggregates (coarse, intermediate and fine), fillers, kaolin, hydrated lime and asphalt binder. The crushed stone angular aggregates (coarse, intermediate and fine), filler and bitumen with performance grade of 80/100 used for asphalt construction were taken from Hossana-Welikite asphalt upgrading project area. The modifiers we have been used is Indian product kaolin and Calcium oxide were purchased from market and sensitive voltmeter was taken from Hawassaa University Department of Physics. The control and modified binder with kaolin and hydrated lime were subjected to laboratory test in order to study their piezoelectric response and rheological properties using sensitive voltmeter and penetrometer. The specimens for compacted asphalt mixture were prepared using all types ingredient with appropriate mix ratio by weight. Then, the density and voids are determined for standard compacted asphalt mixes and modified with kaolin and hydrate lime compacted asphalt mixes. The samples of control, kaolin and hydrated lime modified bitumen asphalt mixture were subjected to laboratory test to compare their mechanical properties using Marshall immersion test method.

Sample Preparations

Initially we looked the standard technique of the contractors was making the Asphalt. Contractor relation with the consultant and also discussed about their mix design and what types of bitumen grade they are using. In my case there were two kinds of design implemented. For mechanical property and piezoelectric property with different proportions of Nanoadditives. Before the preparation of specimens, asphalt mix design was formulated to obtain the appropriate weight ratio of the mixture components. In mix design 19 mm, 14 mm, 9.5 mm, 4.75 mm, 2.36 mm and 0.075 mm sieve sizes were used to find the gradation of aggregate. During the gradation processes, the aggregate passed through 19 mm sieve and retained on 14 mm sieve was taken as coarse aggregate, 9.5 mm sieve passed and 4.75 mm sieve retained was taken as intermediate aggregate, 4.75 mm sieve passed and 2.36 mm sieve retained was taken as fine aggregate, and 0.075 mm sieve complete passed was taken as a filler. After gradation were completed, the appropriate mix ratio (15/20 size=20% coarse, 10/15 size=15% and 5/10 size=15% intermediate, 0/5 size=43% fine and the reaming 7% filler) of the ingredient were found using Job-Mix Formula.

Sample characterizations

For mechanical properties; Based on these result, 1200gm weight of aggregates and 80/100 grade of bitumen were heated to a temperature of 160°C and 150°C respectively. Then, those ingredients were mixed at a temperature of 145°C this was for the standard bitumen. For the preparation of kaolin and hydrated modified bitumen sample, kaolin was heated at a temperature 200°C and Hydrated lime was heated at a temperature of 160°C. The required amount of dried kaolin and hydrated lime was gradually added to the bitumen and dispersed using spatula continuously at a temperature of 145°C for 10 minutes. Then put it in the oven till the temperature reaches 150°C and the mix made with the heated aggregates at 160°C. The percent by weight of asphalt content for all mixes and for kaolin and hydrated lime modified mixes were taken with respect to the total weight of the mixture. The mixture was then placed in the preheated mold and it was then spaded vigorously with the heated spatula 10 times around the perimeter and 7 times in the interior and compacted using 75 blows on both sides of the specimen. Then it was removed from mold. After compaction, the specimen were allowed to cool for 24 hours and removed from the mold by means of an extrusion jack. After removing from the mold, the density and air voids were determined and the specimens was soaked to 60°C water bath for 30 minutes. Then, the specimens was subjected to compression testing machine to measure the(stability) load bearing capacity of specimen and specimen deformation under the load (flow). For piezoelectric response; sample were prepared as usual in mechanical test. Moreover, to make the aggregate uniform we used flakiness test especially 19 mm flakiness pass and 14 mm flakiness retained taken as Angular aggregate. After compaction, the specimen were allowed to cool for 24 hours and removed from the mold by means of an extrusion jack. After removing from the mold brought two equally spaced probes (wire) in contact with a specimen of unknown resistance then the piezoelectric response test were conducted on 0%, 5%, 10% and 15% of kaolin and hydrated lime modified bitumen asphalt at room temperature by means of sensitive voltmeter and compression testing machine at Welikite- Hossana asphalt upgrading Project.

Rheological Analysis Tests on Standard and Modified binders

The Marshal Test method were conducted to analyze the mechanical properties of modified bitumen asphalt; such as penetration with control and modified mix design. The penetration test is an empirical test used to measure the consistency of bitumen asphalt. It was used to determine the grade of bitumen asphalt. In performing the test on control and modified binder with hydrated lime and kaolin content of 5%, 10% and 15%. For the preparation of kaolin and hydrated modified asphalt sample, kaolin was heated at a temperature 200°C and Hydrated lime was heated at a temperature of 160°C. The required amount of dried kaolin and hydrated lime was gradually added to the bitumen and dispersed using spatula continuously at a temperature of 145°C for 10 minutes. After mixing the specimen were allowed to cool for 24 hours then put it in the bath till the temperature reaches 25°C. After that the needle is carefully brought to contact with the surface of the sample, then released so as to exert a pressure of 100 gm for 5 seconds at 25°C temperature scale. At 5 seconds after the needle was released, we read on the penetrometer dial how much distances the needle penetrate the sample. In this study, three penetration measurements were taken for each sample and the average value of penetration was calculated for each specimen.

RESULTS AND DISCUSSION

This part presents the experimental results obtained in present work. In the first section of the chapter the binder properties, the effects of hydrated lime and kaolin additives on piezoelectric response were discussed and in the second section discussed about mechanical properties of modified asphalt. Mechanical properties of HMA depend upon the binder type, the sizes and gradations of the aggregates and the filler, the type of mineral additives, and the proportions by weight of each of the component of the mix and the percentage of air voids. The mechanical properties of the binders were determined through penetration test. The test was performed in order to identify the dependability of binders. After that the actual Marshall stability, flow test was made on the modified bitumen asphalt.

Rheological Tests on Standard and Modified Bitumen Asphalt

Penetration Test

Table 1 display percentage of kaolin and hydrated lime content in bitumen at 25 C. As can be seen from the figure the penetration depth of the kaolin modified binder reduce from 5% to 10% and increase when increased to 15%. At 5% of kaolin content modified bitumen reduces penetration rate by 11.7%, compared with 82.9 penetration range of standard mix. Furthermore, kaolin usually exhibit aplastic behavior, is adhesive when moist and stiff when dry. This is why; mixing a few percentage of kaolin in bitumen leads to increases its consistency and decreases the penetration depth. Table 4.1 also shows that the effects of hydrated lime content at 5%, 10% and 15% on the consistency of bitumen with 80/100 penetration grade. It may be observed that the penetration depth lower when the concentration of hydrated lime is higher. Lower penetration indicating harder bitumen used in warm region. The overall result shows the penetration depth were between 80/100. Better result was observed by adding 15% of hydrated lime in to the standard bitumen (0%) relative to 5% and 10%.

Piezoelectric Response Testing of Specimen

Table 2 demonstrates the effect of 5%, 10% and 15% of kaolin content on voltage change of modified bitumen. As we can see the voltage change increases with the kaolin content in bitumen from 5% to 10%. This effect can be attributed to kaolin, that has an overall negative charge (Dallas et al., 2001), when a load (compression force) exert on it the charge start vibrating create an electric field that field separate the charges that produces voltage, but the voltage change decreases as the concentration of kaolin increasing to 15%. This may be due to the addition of high concentration of kaolin change the occurred may be due to bitumen structure. The bitumen structure consists of Polar and non-polar group; Polar groups are formed by the various combinations of heteroatoms (N, S, O and metals) within bitumen and have electropositive and electronegative characteristics (Zoltán and József F, Bentonite, 2005). Even a small amount of hydrated lime addition in polar group changes the characteristics and behavior of bitumen with aggregate surface. In polar bonds a highly electronegative atom bonds to a less electronegative atom because N, O, S and metal contribute polarity within the molecules, the presence of polarity in pavement structure may create an electric field when load exert on it. This field enforces charge to flow in asphalt pavement. Table 4 demonstrates the voltage change with the same amount of increment in hydrated lime and kaolin content at 5% and 10% but at 15% kaolin content drastically reduce its voltage. It may be observed from this figure the voltage change

Table 1. Penetration tests on standard and modified bitumen with different kaolin and hydrated lime content at 25°C

No of Trial	Kaolin content (%)	Penetration (0.1mm)	Average	Hydrated lime content (%)	Penetration (0.1mm)	Average
1		80.0			80.0	
2	0.00	83.5	82.9	0.00	83.5	82.9
3		85.2			85.2	
1		77.5			89.4	
2	5.00	67.4	73.2	5.00	90.6	89.4
3		74.6			88.3	
1		67.7			89.9	
2	10.00	71.2	69.9	10.00	84.0	86.6
3		69.9			85.8	
1		68.1			83.2	
2	15.00	77.0	71.0	15.00	84.3	84.4
3		67.7			85.8	

Table 2. Voltage change in kaolin modified sample test at room temperature

% of Ac by total mix	% of kaolin content by weight of bitumen	Piezoelectric response (v) At 0.076KN average force
5.1	0%	0.0010
4.8	5%	0.0027
4.6	10%	0.0055
4.3	15%	0.0033

Table 3. Voltage change in hydrated lime modified test at room temperature

% of Ac by total mix	% of hydrated lime content by weight of bitumen	Piezoelectric response (v) At 0.076KN average force
5.1	0%	0.0010
4.8	5%	0.0028
4.6	10%	0.0033
4.3	15%	0.0035

Table 4. Comparison of voltage change on hydrated lime and kaolin content

% of Ac by total mix	% of modifier content by weight of bitumen	Piezoelectric response (v) At 0.076KN Average force	
		For Hydrated lime content	For kaolin content
5.1	0%	0.0010	0.0010
4.8	5%	0.0028	0.0027
4.6	10%	0.0033	0.0055
4.3	15%	0.0035	0.0033

minimum delocalization impurity concentration increases/ lower the moment of dipole when pressure exert on it, that leads to electrical resistance, hence electron have fewer possibilities to flow in one direction.

Table 3. Shows the effect of 0%, 5%, 10% and 15% of hydrated lime content on voltage change of bitumen with 80/100 penetration grade. As can be seen from Table 4.3 voltage increases as the hydrated lime content in bitumen increases from 0% to 15%. The overall result shows some improvement relative to the control bitumen mix. This of hydrated lime modified bitumen at 5% and 15% increased by 3.6% and 5.7% respectively than that of kaolin modified bitumen, but at 10% the voltage change of kaolin modified bitumen drastically increased in many order (40% higher than that of hydrated lime modified bitumen).

Performance Tests on control and Modified Bitumen Asphalt

The results of Marshall Tests on control mix, hydrated lime and kaolin modified bituminous mixes prepared at various hydrated lime and kaolin contents by total mix are given in Table 4. In this section tests performed on modified with different hydrated lime and kaolin content and control asphalt mixes and the comparison of the test results to see the effect of the hydrated lime and kaolin content of 0%, 5%, 10% and 15% modification on the performance of the asphalt mixture were discussed.

Bulk Density of Compacted Specimen

In Figure 1 the effect of hydrated lime and kaolin content on the bulk density of compacted mixes is shown. Modification made with hydrated lime shows a trend of decrease the bulk density of the compacted mixture as the amount of hydrated lime content in the mixes increases from 5% to 10% and increases when increased to 15%, but the bulk density of the compacted mixture increases as the amount of kaolin content in the mixes increases, this is may be due to kaolin lubricates the particles allowing the compaction effort to force them close together. However, the control compacted asphalt sample has higher bulk density compared to kaolin and hydrated lime modified sample.

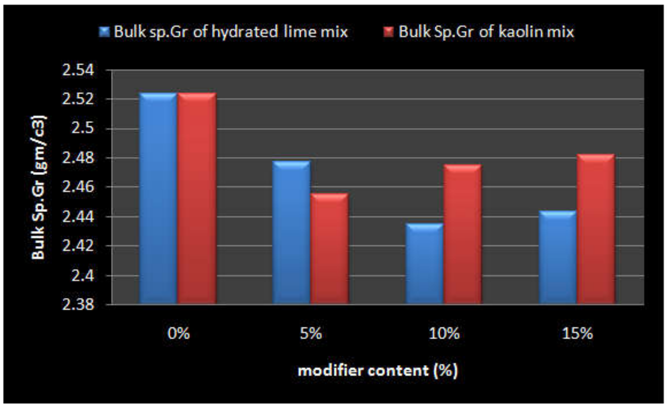

Figure 1. Effect of different HL and kaolin content on bulk density

Maximum Specific Gravity of Compacted Specimen

Figure 2 shows the effects of different hydrated lime and kaolin content on the maximum specific gravity of compacted specimen. In theory, the maximum specific gravity of paving mixture decreases as the bitumen content in the mixes increases (Lemma *et al.*, 2012). Result of the present work showed that the control paving mixes have the same maximum specific gravity at 5% of hydrated lime content. Otherwise the control paving mixes have maximum specific gravity than that of kaolin and hydrated lime modified asphalt. Further it may be observed from fig 4.7 the maximum specific gravity varies as the kaolin and hydrated lime content in the mixes increases. This is attributed to temperature difference when mixing kaolin and hydrated lime content with standard mix bitumen.

Air Voids of Compacted Specimen (Va)

Figure 3 shows the relationship between the voids percent in total mix and asphalt content for control, hydrated lime and kaolin modified mixes. It can be noticed that percent of Va decreases with increasing of Asphalt content. Also, it can be noticed that percent of Va for hydrated lime and kaolin modified mixes is higher than that of control mixes for 5% to 10% of hydrated lime and 10% to 15% of kaolin content. The hydrated lime content at 15% and kaolin content at 5% percent of air void showed decrement. As the bitumen content in the compacted mixture increases, bleeding of bitumen may occur at high temperature and leads asphalt to permanent deformation. But if the required amount of air voids are there, the bleed bitumen at high temperature may fills the air voids and resists asphalt from permanent deformation.

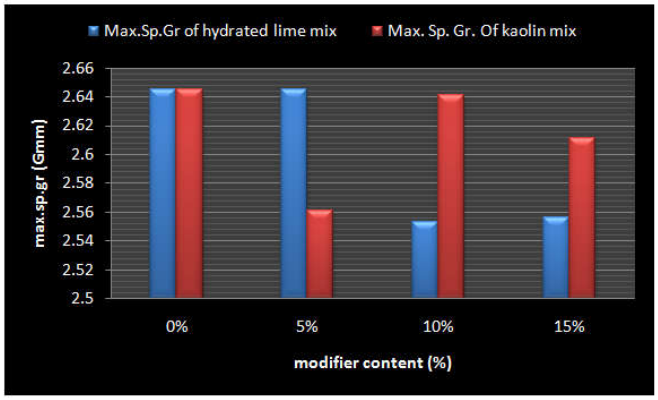

Figure 2. Effect of different HL and kaolin content on maximum specific gravity of Compacted specimen

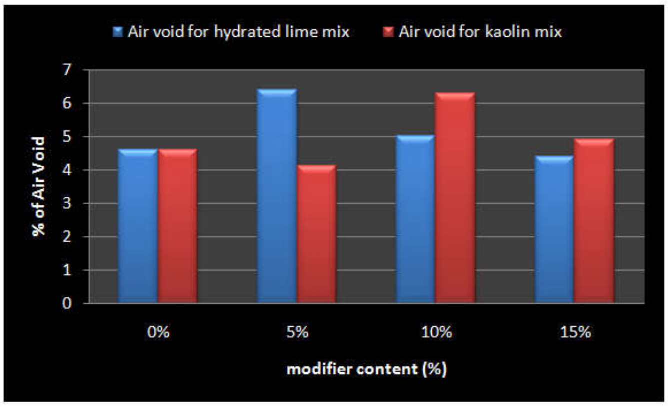

Figure 3. Effect of different hydrated lime and kaolin content on air voids

Voids in Mineral Aggregate (VMA) of Compacted Specimen

The effect of hydrated lime and kaolin on voids in mineral aggregate was also discussed and the results are shown in Figure 4.

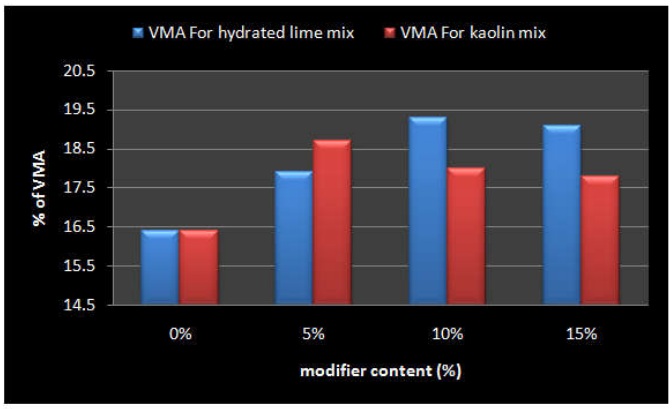

Figure 4. Effects of different H.L and kaolin content on voids in mineral aggregate

In modified mixtures, the voids in mineral aggregates decrease as the kaolin content in the mix increases and increase as hydrated lime content increases from 5% to 15% then attained lower value at 5%. The values of VMA in kaolin and hydrated lime modified compacted asphalt mixes should have a minimum requirement and accepted percentage of VMA is greater than 14%. It is obvious that a minimum VMA requirement is necessary to ensure that the mix is not deficient in asphalt cement. In the present case both hydrated lime and kaolin modified mixture meet the minimum requirement.

Void Filled with Asphalt (VFA) in Compacted Specimen

Figure 5 shows voids filled with asphalt (VFA) percent versus asphalt content for various mixes. It may be observed from this figure the hydrated lime content at 10% and 15% the VFA value is higher than that of the control mixes, however at 5% lower by 10.8% and by 1.2% compare to control mix and the Minimum Marshall criteria respectively. For kaolin content the VFA value at 5% and 15% of kaolin modified mixes is higher than that of the control mixes, however at 10% decrease by 9.7% compare to control mix but it is within in the range of Marshall criteria. The Marshall criteria for voids filled with asphalt is between 65% - 78%. If the percentage of voids filled with asphalt is lower than the limit indicated, there will be less asphalt content around the aggregate particles. Hence, affects the durability and locking of aggregates to each other

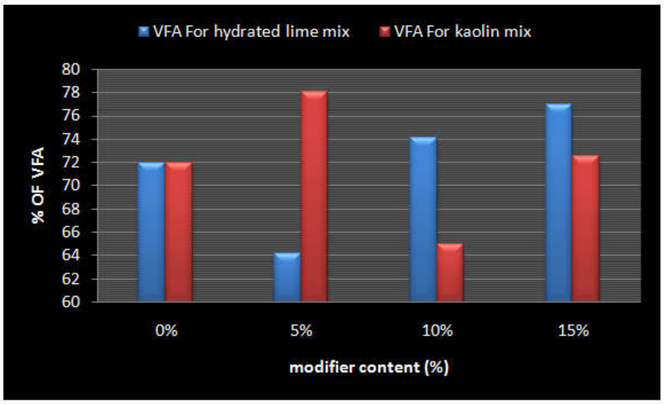

Figure 5. Effects of different HL and kaolin content on VFA

Marshall Stability of Compacted Specimen

Figure 6 shows the Marshall Stability values for control, hydrated lime and kaolin modified mixes versus asphalt content. The Figure shows that for the same hydrated lime and kaolin content, Marshall Stability for kaolin modified mixes is higher as compared with control and hydrated lime mixes .It indicates that Marshall stability of modified mixes increases as the percentage of kaolin content increases. But in hydrated lime content at 5% stability attained maximum after which stability tends to decrease from 10% to 15%. The largest value of stability occurred at hydrated lime and kaolin content of 5% and 15% is 15.81KN and 17.16 KN respectively while the maximum stability occurred at standard mixes is 13.4 KN.

Marshall Flow of Compacted Specimen

Figure 7 presents Marshall Flow values with respect to asphalt content. It is clear that flow value of kaolin modified mixtures increase as the content increases this is may be due to the plastic behavior of kaolin. But the flow value of hydrated lime mixtures decrease as the hydrated lime content increase.

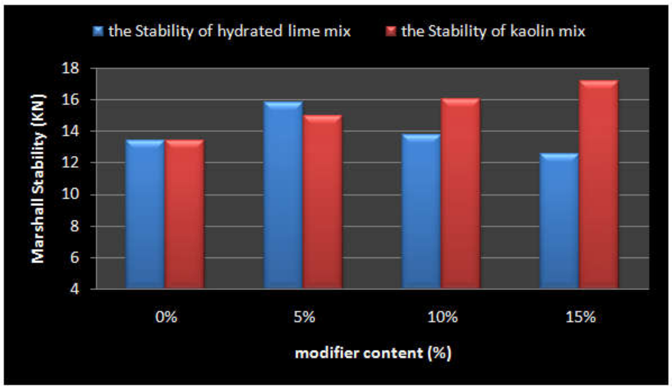

Figure 6. Effects of different HL and kaolin content on Marshall Stability

The result also showed that the modified mixes gives higher values of Marshall flow than control mixes.

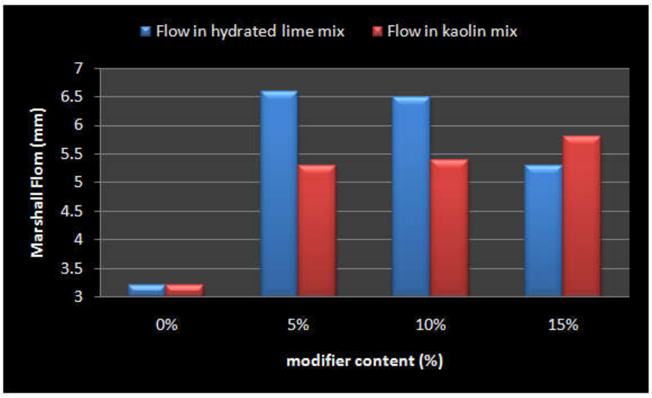

Figure 7. Effects of different HL and kaolin content On Marshall Flow

Table 5. Effects of different Hydrated lime and kaolin content on Stiffness

% of Ac by total mix	% of modifier content by weight of bitumen	Stiffness for Compacted Specimen	
		for Hydrated lime content	For kaolin content
5.1	0%	4.2	4.2
4.8	5%	2.4	2.8
4.6	10%	2.1	2.97
4.3	15%	2.37	2.96

Calculation of Stiffness for Compacted Specimen

Table 5 shows the Stiffness value for control, hydrated lime and kaolin modified mixes versus asphalt content. The stiffness is calculated as, Stiffness = Stability/flow. The table shows that for the same hydrated lime and kaolin content, Stiffness for standard mixes is higher as compared with kaolin and hydrated lime modified mixes. It indicates that stiffness of modified mixes increases as the percentage of kaolin content increases from 5% to 10% and reduces when increased to15%. But in hydrated lime content at 5% stiffness attained maximum after which stiffness tends to decrease from 5% to 10% and increases when increased to 15%. When this modified mixture is loaded with a load level higher than maximum load level, some additional permanent deformation will be developed. If the load level is less than the previous load level, an elastic response will be observed.

Calculation of Optimum Asphalt Content for Control and Modified Mixes

The optimum asphalt content of the various mixes is determined from Marshall Property (stability, bulk density, and air voids in total mix). It is the numerical average of the percentages of the asphalt content determined corresponding to maximum Marshall stability, maximum bulk density, and medium range of voids in total mix (Dallas *et al*., 2001) thus,

$B_0 = (B_1+B_2+B_3)/3$

Where,

B0 = optimum Bitumen content.
B1 = % asphalt content at maximum unit weight.
B2 = % asphalt content at maximum stability.
B3 = % asphalt content at specified percent air voids in the total mix.

Optimum asphalt content for kaolin modified bitumen is calculated as

Maximum stability = 17.16 KN, at bitumen content = 4.3%
Maximum bulk density = 2.482gm/cc, at bitumen content = 4.3%

Percent air voids = 4.1%, at bitumen content = 4.8%,

The optimum asphalt content for standard mix is 5.1 while for the modified mixes is 4.3 and 4.8 for (15% and 5% kaolin content) respectively. Hence, optimum bitumen content of kaolin modified bitumen = 4.5% (at kaolin Content=11.7%).

The optimum asphalt content for HL modified bitumen is calculated as
Maximum stability = 15.81 KN, at bitumen content = 4.8%
Maximum bulk density = 2.477gm/cc, at bitumen content = 4.8%
Percent air voids = 4.4%, at bitumen content = 4.3%.
The optimum asphalt content for standard mix is 5.1 while for HL modified mixes is 4.3 and 4.8 for (15% &5% HL content respectively). Hence, optimum bitumen content of HL modified bitumen = 4.6% (at HL content= 8.3%).

Recommendation

Piezoelectric response in hydrated lime and kaolin modified bitumen asphalt is an active area of research. Hence, further studies are recommended on different aggregate shape, temperature, binder grade of kaolin and hydrated lime modifier before designing self-sensing asphalt.

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