WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.140192

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 1 2022

 pp. 653 –666

Research paper

Properties of stone mastic asphalt incorporating nano titanium as binder's modifier

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Abstract: Stone mastic asphalt is a gap-graded mix and is usually related to its high bitumen content and its skeleton-like constitution. Although famous for its durability, high resistance to fatigue and rutting, issues such as bleeding and premature aging do occur in the mix since it has a high bitumen content and voids due to its gap-graded structure. In order to encounter these problems from affecting the mix, some instances such as adding additives, rejuvenators and stabilizers into the mixture has been implemented.

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Nowadays, nano materials are being used in the asphalt mixtures and nano titanium is being introduced as a modifier to the asphalt binder in order to improve the mechanical properties of the stone mastic asphalt mix. The related tests done in order to access the improvement are resilient modulus, dynamic creep, moisture susceptibility and binder drain down. The content of nano titanium used in this research are 1%, 2%, 3%, 4% and 5%. This study is done to assess the mechanical performance of stone mastic asphalt with nano titanium modified binder.

Keywords: stone mastic asphalt, nano titanium, binder draindown, moisture susceptibility

1. Introduction

Flexible pavement is made up of asphaltic or bituminous materials spread over the surface course and most part of flexible pavement is made up of mix of both fine and coarse aggregates [1]. As the name implies, it acts like a sheet of paper when a load is exerted on the pavement thus it will bend and will return to its original nature after the load has been released. Since flexible pavement possess low flexural strength, overexertion of load may lead to pavement deformation [2]. Rutting and fatigue are among the issues commonly faced by flexible pavement and there are a number of factors pertaining to these issues. There are different types of flexible pavement available which are Dense Graded Asphalt, Porous Asphalt, and Stone Mastic Asphalt.

Stone Mastic Asphalt or SMA appeared in the mid-1960s due to the usage of studded tires in Germany. SMA was introduced to withstand the damage inflicted by the design of the tires but when the tires were scrapped to use, it caused SMA production to come to a halt. SMA usage resurfaced in the US during the 1990s was secondary to the efforts taken by legislative bodies to compile and come out with a standardized code involving the use of SMA in designing pavements with high traffic capacity which is now being adapted and used globally [3]. Stone mastic asphalt is a gap graded asphalt as the two main components are the high content of coarse aggregate which is approximately 70% to 80% of the whole mix alongside with a high content of bitumen and the filler. The coarse aggregate content provides stone on stone contact, making SMA more durable than conventional pavement. The high bitumen content completes the mix with an additional additive like cellulose fiber in order to prevent problems like bleeding in the mix [4]. According to [5], the optimum binder content of stone mastic asphalt is about 6.16%.

Since it has a gap graded structure with a significant amount of coarse aggregates, these aggregates make a skeleton-like structure thus, providing a durable structure. Stone mastic asphalt is able to resist deformation and fatigue better and longer than the traditional asphalt mix. Other advantages of stone mastic asphalt includes stability at high temperature, increased wearing resistance, malleable at low temperature and increase of adhesion which helps inhibit the separation of particles [6]. Other than that, stone mastic asphalt shows better performance in skidding, lesser noise emittance, and helps to enhance night vision. This type of mix is suitable for heavy traffic area as heavy loads are stone mastic asphalt's specialty [7]. Heavy traffic will impose more load on the road and stone mastic asphalt could endure the loads because of the strong adhesion between the bitumen and aggregate [8]. This is why stone mastic asphalt is used as a wearing course.

Stone mastic asphalt do possess a few disadvantages. Issues such as binder drain down, high production cost, rutting and moisture susceptibility have been commonly raised as the downside of SMA usage despite its excellent performance in sustaining heavy loads. Binder drain down happens when the bitumen drains off from the aggregate to the bottom at the times when placing, production and storage [9]. Since the structure is gap graded with high bitumen mastic, the voids between the aggregates contributes to binder drainage. Thus, stabilizers like cellulose fibers and polymers are added to prevent the mix from excessive bitumen drain off [10]. Production process of stone mastic asphalt can hike up in cost since the polymers used in the mix is hard to obtain. Next is rutting in stone mastic asphalt. It starts with a small crack from the bottom layer of the mix and more cracks would eventually form. These cracks then connect and rutting would occur at the top layer of the pavement. The repetitive loading of vehicles adds up to the formation of rutting since the load exceeds the capability of the pavement [11]. Eventually, these could lead up to another problem which is moisture susceptibility. Moisture susceptibility or moisture resistance happens when water seeps in through the voids present, making the adhesion between aggregates and bitumen to gradually loosen and finally separated [12]. Potholes could also be formed due to this phenomenon.

Nanomaterials are chemical compounds or products that are processed and used on a very small scale. The size of nanomaterials is between 1 to 100 nanometers (nm). A few examples of nanomaterials are titanium dioxide, silica oxide, graphene oxide and aluminum oxide [13, 14]. Nanomaterial has been used in various fields such as healthcare, beauty products, biology related field as well as construction before extending to pavement industry. Due to their high surface area and miniscule size compared to normal additives, nanomaterials exhibit special characteristics when used in a mixture moreover with a decent amount. There are two methods of producing nanomaterials, namely, the top-down approach and the bottom-up approach [15]. The top- down approach consists of two methods. In the ?rst method, bigger structures are diminished in size until they reach nano-scale while the second approach consists of deconstruction into nanomaterial composite parts [16]. This is where the surface modified nanomaterials like nano silica, nano zinc oxide and nano titanium acts as they could improve the anti-aging behaviors of asphalt.

Due to this, various research regarding SMA improvement has been explored using materials with abilities to reduce binder drain down, asphalt aging, permanent deformation, fatigue, low temperature cracking and economic issues are considered [5]. Thus, this research is done to investigate the mechanical performance of Stone Mastic Asphalt incorporating nano titanium modified binder.

2. Application of nano materials

Aging is indeed a concern when it comes to asphalt mixture, where there are two types of aging, namely thermal oxidative aging and photo-oxidative aging. This is where surface modified nanomaterials such as nano silica, nano zinc oxide and nano titanium play an important role as they possess the ability to enhance the anti-aging behaviours of asphalt [17]. Nanomaterials could increase the roughness and adhesion of asphalt mixtures.

Nano clay is a naturally occurring mineral where its purity has the potential to affect the final nanocomposites properties. Due to their low cost of production, it is commonly used as it has potential to improve mechanical and thermal binder properties [18]. Nano silica properties such as good stability, affordable cost, high surface area, chemical purity and good dispersing ability has made it one of the most used materials over the years in improving mechanical performance of asphalt such as aging, fatigue and cracking [19]. The following Table 1 shows some of the effects of using nano materials.

Table 1. Effects of using nano material in previous researches

Nanomaterial used	Content (%)	Aging time	Aging temperature (°C)	Observed effect	References
Titanium dioxide/ montmorillonite	4–6	336 h	–	5 % is the best UV aging resistance for the bitumen	[20]
Zinc oxide	2–3	6 d	80	3 % shows the best anti-aging performance	[21]
Mg–Al–CO_3 layered double hydroxides	3	9 d	60	Layered double hydroxides with 180 nm possess the strongest ability to absorb and reflect UV light	[22]
Clay	1–3	12 d	60	2% improved the anti-aging resistance	[23]
Graphene oxide	0.5–1.5 wt.%	9 d	50	1.5 wt.% has the best anti-aging performance	[24]
Zinc oxide	1–5 wt.%	400 h	–	3% ZnO is the optimum content	[25]

Nano titanium dioxide (Nano TiO_2), exists in three phases which are anatase, rutile and brookite in which anatase shows the most stable and high photocatalytic activity. Nano titanium dioxide is synthesized by sol-gel method, it possesses self-cleaning and self-sanitizing properties since it is considered as an active photo-catalyst [26]. Since UV oxidation affect asphalt in high altitude region, nano titanium dioxide application could encounter asphalt aging faster than other nanomaterials. The use of nano titanium dioxide is also applied in dental care as implants since it enhances protein adsorption, cell differentiation and surface bioactivity [27]. Food stimulants are involved with nano titanium dioxide as it is one of the materials involved in making food packaging. In this study, nano titanium obtained from Gardner Global is used.

3. Materials

3.1. Asphalt binder

The bitumen used is of 60/70 penetration grade according to Public Work Department specification of bitumen to be used in stone mastic asphalt mix (Table 2).

Table 2. Physical properties of Bitumen Grade 60/70

Properties	Descriptions
Specific gravity at 25°C	1.01/1.06 kg/cm^3
Penetration at 25°C	60–70 mm/10
Softening Point at 25°C	49–56°C
Ductility at 25°C	100 cm

3.2. Nano titanium

Nano titanium from Gardner Global is used. The nano titanium appears in a white powdery form. Table 3 shows some of its basic properties.

Table 3. Physical properties of nano titanium

Properties	Values
Colour	White
Purity (%) White	99.9
Primary particle size (nm)	21
Structure	Anatase, Rutile, Brookite
Melting point	1843°C
Boiling point	2972°C
Relative Density at 25°C	4.26 g/cm^3

3.3. Aggregate

Aggregate used in this was a type of granite from the local quarry in Pahang, Malaysia. The sizes are ranging from the maximum size of 20 mm up to filler/quarry dust. The certain amount of filler was also replaced by up to 2% of Ordinary Portland Cement (OPC) to reduce the stripping issue for each compacted PA specimen. Since filler was just a small amount, it may not affect the overall performance of the PA specimen.

4. Experimental methods

4.1. Resilient modulus

Resilient modulus test is crucial to determine material stiffness under different conditions according to ASTM D 4123.The test was conducted at two different temperatures which are 25°C and 40°C. The temperatures indicate middle and high temperature condition. The Universal Testing Machine (UTM) is computer-automated and the software used is ITS-Resilient Modulus. Before running the software, the axial force must be offset to zero to prevent the knob from going upward by itself.

There are two variables that relate to the software used which are the linear variable differential transducers 1(lvdt1) and linear variable differential transducers 2 (lvdt2). They cannot be in negative value before the test is conducted to prevent reading inaccuracies. The test would take approximately 3 hours to complete per specimen. A total of 2 samples for each amount of nano titanium were prepared and tested with 2 test temperatures. In addition, the sample were also tested in two position which are 0 and 90-degree position to obtain more accurate results. Then, the average reading was taken for each specimen.

4.2. Dynamic creep

This test is done to evaluate the rutting resistance of asphalt pavements according to ASTM D704-15. This test was done by using the Universal Testing Machine (UTM) and a software of permanent deformation on the computer. The samples were prepared according to Marshall Mix Design with reference to JKR/SPJ/S4. The sample is compacted by using a Marshall compactor with 50 blows on each face. The optimum binder used is 6.16% according to [5]. The sample would then be conditioned at a temperature of 40°C in the UTM before being placed into the dynamic creep apparatus. The testing occurred for about 2 hours before the end result is produced on the computer.

4.3. Moisture susceptibility

The test is done according to AASHTO T-283. All the samples possess the same diameter with different heights. The samples were prepared in two conditions which are wet and dry conditions. A total of 16 samples, 8 for dry conditions and 8 for wet conditions. The dry sample is conditioned for 2 hours at 25°C while the wet sample was left in a water bath for 24 hours at 60°C and continued for 2 hours at 25°C. The samples were tested by using the Indirect Tensile machine and the result were recorded.

4.4. Binder drain down

The samples involved are 0%, 2%, 3% and 4% of nano titanium modified bitumen. A loose sample of 1200 g of stone mastic asphalt is heated in the oven for about 24 hours prior to the test. The sample is then mixed with respective amount of nano titanium modified bitumen and later deposited into a square basket. It is then placed into the oven for approximately 3 hours. The weight before and after is recorded and observed. The loss of weight is noted as the binder drain down.

5. Results

5.1. Resilient modulus

The results of resilient modulus at 25°C show an increasing trend when nano titanium is added. After reaching its optimum content, the resilient modulus value of the sample shows a decreasing value. This trend is consistent with a study by [14] and [29] in which with the modification of the asphalt binder improves the resilient modulus value significantly [30]. For the resilient modulus value of the nano titanium modified sample, the pulse repetition periods used are 1000, 2000 and 3000 ms respectively. From Fig. 1, the sample with 3% nano titanium modified binder has the highest resilient modulus with 1478 MPa compared to 0% sample with 1473 MPa. The same is observed with 2000 pulse repetition where 3% is the highest with 1903 MPa while 0% nano titanium modified binder only reaches up to 1311 MPa. When the 3000 pulse is applied, the values of resilient modulus for 0% and 3% nano titanium modified binder are 1424 MPa and 1521 MPa respectively. The nano titanium helps the mixture to resist horizontal deformation. Moreover, the presence of nano titanium in the voids between the aggregates may strengthen the mix. These results show that the resilient modulus values are increasing compared to the control sample thus proving the improvement of resilient modulus of the sample.

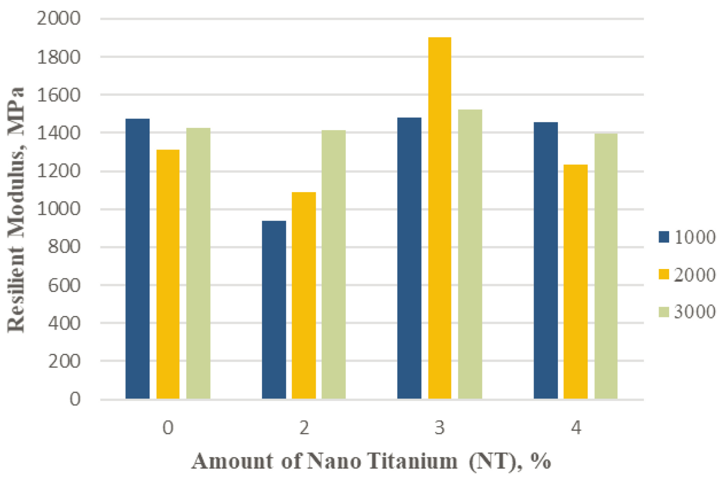

Fig. 1. Resilient modulus of Asphalt Mixtures at Different Dosages of Nano Titanium at 25°C

Figure 2 display the resilient modulus of the samples but at a temperature of 40°C. The strength of the samples with increasing temperature also relates with a study by [31]. As can be seen, with each increasing addition of nano titanium, the strength also shows an increasing trend for each of the pulse repetition period. The most significant one would be 3% nano titanium modified sample. The resilient modulus value for 0% and 3% is 1453 MPa and 2410 MPa at 1000 pulse repetition. Followed by 0% and 3% with 1438 MPa and 2172 MPa, the resilient modulus value keeps increasing up until the 3000-pulse repetition. It could be seen with their values 2081 MPa (0%) and 2248 MPa (3%). The highest value is observed for each of the pulses at 3% nano titanium modified sample.

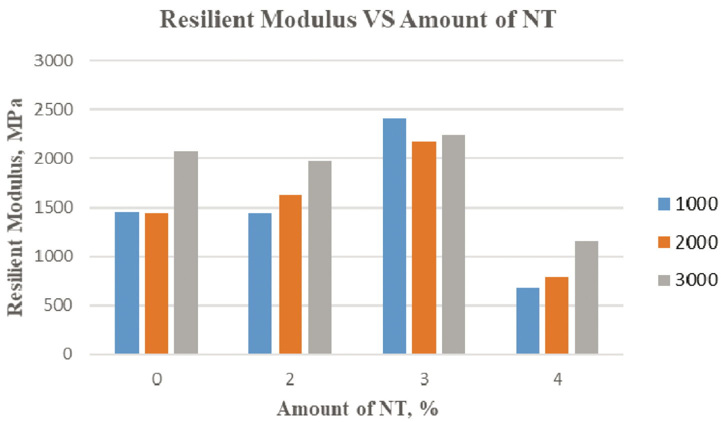

Fig. 2. Resilient modulus vs Amount of Nano Titanium at 40°C

The temperature plays an important part. This is apparent as the temperature increases; the resilient modulus also increases. However, after adding more nano titanium, the strength decreases. This validifies that the modifier content and temperature does have an effect to the resilient modulus value. This is also related with the temperature sensitivity aspect of the sample. Since the nano titanium is related to higher specific surface area, the interaction between the asphalt binder in the mix is larger when nano titanium is present in comparison to unmodified bitumen.

It shows that with the inclusion of 3% nano titanium modified binder, the resilient modulus of the sample is improved compared to the control sample as compared to the unmodified asphalt which have the lowest resilient modulus at 2081 MPa, 3% nano titanium modified binder is the highest with 2248 MPa. The increase in modifier content promotes improvement of elastic properties in the asphalt mixture. The sample at 3% nano titanium modified binder then shows that at a higher temperature, the sample is more resilient to damage. Since the resilient modulus value increase, the elasticity also increases, resulting in better damage resistance compared to unmodified sample.

5.2. Dynamic creep

Figure 3 presents the permanent deformation illustrated by the permanent strain vs cycles graph between modified and unmodified samples. There is a significant difference in the amount of nano titanium content in the samples. There are three stages of creep, which are the primary stage, secondary stage and tertiary stage. The samples observed are showing primary stage up to 1200 cycle where elastic strain occurs and secondary stage after the 2400 cycle where viscoelastic strain by axial stress. The results imply that the mixtures containing certain amount of nano titanium modified asphalt binders have higher resistance against deformations. The sample with 3% nano titanium shows a reduced resistance against deformation compared to the 2% nano titanium modified sample since it might not have enough composition to resist deformation. At 4% addition of nano titanium, the sample has higher strains value compared to the control sample. Thus only 3% addition of nano titanium produces satisfactory result as at early strain it has less strain compared to the control sample. Thus only 3% addition of nano titanium produces satisfactory result as at early strain it has less strain compared to the control sample. This align with [29] findings which mentioned that asphalt resistance to permanent deformation is lesser if the value of permanent strain is lower.

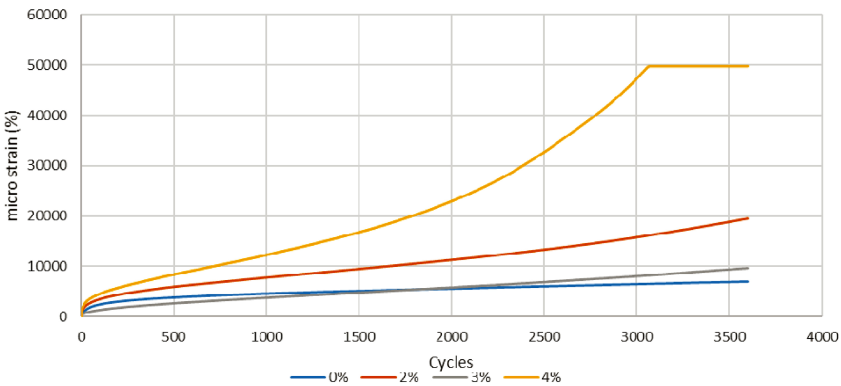

Fig. 3. Strain Values for each modified SMA Specimen

5.3. Moisture susceptibility

The Indirect Tensile Strength (ITS) value is calculated after the Maximum Applied Load from the Modified Lottman Test is obtained. The values from dry condition is more than the wet condition, similar to studies conducted by [32] and [33]. From Fig. 4, the highest ITS value for the dry condition is at 2% which is 276 kPa followed by 4% (264 kPa) and 3% (174 kPa), For the wet sample, the same trend is observed with 2% (226 kPa), followed by 4% (195 kPa) and 3% (189 kPa). Indirect Tensile strength represents the cracking resistance, the ability of a mix to withstand cracking will improve with higher value of indirect tensile strength. From the ITS value, it could be seen that the samples at wet condition has less indirect tensile strength than the samples at dry condition, which means that there is a presence of moisture. With this, the tensile strength of the mix is reduced, making it more susceptible to potential cracking. Since the mix possess voids from its use of coarse aggregates the gaps between them would enable moisture to seep into the mixture. This would influence the strength of the mixture and it is seen that the presence of moisture does affect the performance of the mix. Figure 5 also shows the Indirect Tensile Strength Ratio (ITSR) value of 3% is heightened due to the inclusion of nano titanium in the mix.

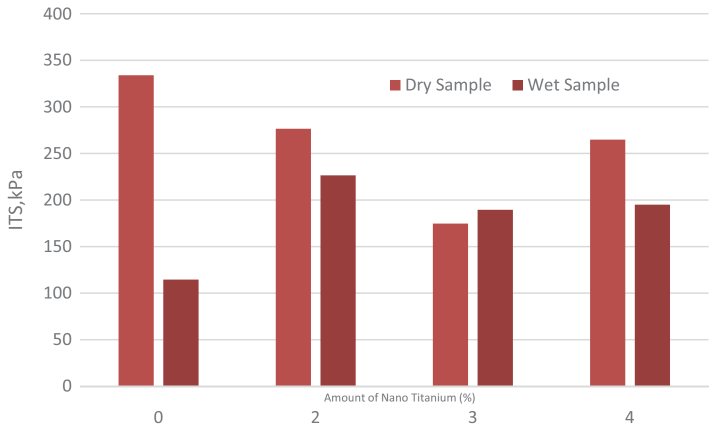

Fig. 4. ITS Value vs Amount of Nano Titanium

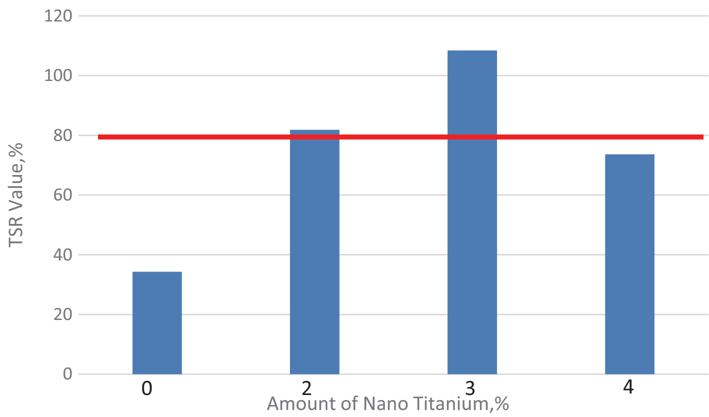

Fig. 5. ITSR Value (%) vs Amount of Nano Titanium (%)

5.4. Binder drain down

Figure 6 shows the binder drain down for each percentage of nano titanium modified bitumen, with 2% nano titanium modified binder having the lowest binder drain down value followed by 4% and 3% nano titanium modified binder specimens. The binder drain down refers to the bitumen flowing out during mixing of a mix, since SMA has a high content of bitumen as a filler and has a gap graded composition, it is prone to binder drain down.

The binder could flow through the small gaps present making way for the binder loss. As seen on control specimen (0% nano titanium modified binder), there is quite a number of excess bitumen flowing out during the mixing. Thus, this could affect the condition of the mix. The nano titanium added into the bitumen would make the bitumen harder, making the particles of the bitumen to be more intact with each other and will not easily flow through the aggregates since it will hold the aggregates better, preventing excess drain of bitumen. With the addition of nano titanium, the mix shows a reduced amount of binder drain down significantly this align with a study by [28].

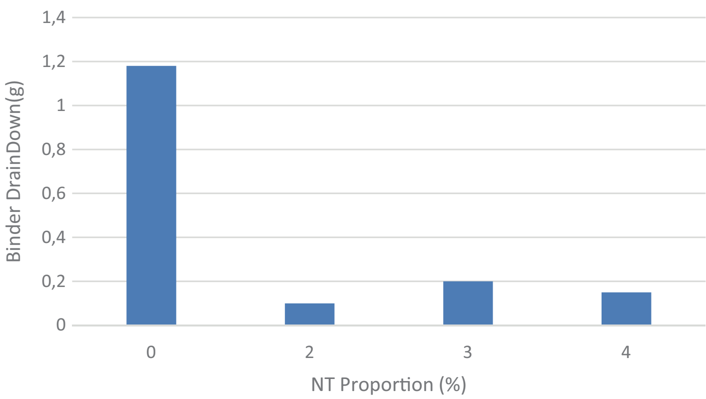

Fig. 6. Binder drain down vs Nano Titanium

6. Summary and conclusions

Based on the results shown, there are improvements in terms of mechanical performance of stone mastic asphalt:

- Resilient modulus at 25°C shows the sample with nano titanium included have better higher values of stiffness modulus compared to the control sample without nano titanium. The presence of 3% nano titanium in the mix influence the stiffness modulus of the SMA mix.
- At 40°C, the temperature represents the high temperature condition and it also shows the same trend as previous temperature, in which the resilient modulus value at 3% shows a better strength compared to the sample without the presence of nano titanium.
- For dynamic creep, the strains generated are mostly related to primary and secondary stage. At 3% the permanent strain is acceptable compared to 4% which indicates that the sample undergoes failure.
- The ITS and ITSR results show that, with 3% nano titanium modified binder the moisture susceptibility is improved. The presence of moisture is prominent since the dry sample which have a large amount of strength earlier, has reduced strength after being exposed to moisture.

- The binder drains down also show a great improvement at 3% nano titanium modified binder. The amount of binder drains down for control sample is the highest while 3% nano titanium shows the lowest drain down value. So, it can be seen that with the addition of nano titanium, the binder drains down could be lessened.
- At 3% addition of nano titanium, the result for each test shows better results compared to the control sample.
- Further research is recommended in terms of conducting more related tests in order to assess the influence of nano titanium.

Acknowledgement

The authors would like to express deeply gratitude to Universiti Malaysia Pahang and Ministry of Higher Education for funding this research under Grant No RDU1903146 and PDU203206.

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Received: 10.11.2021, Revised: 7.12.2021