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Effect of aging and moisture damage on the cracking resistance of rubberized asphalt mixture

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ABSTRACT

The use of crumb rubber to modify asphalt mixtures has astounding economic and environmental benefits. However, the use of asphalt mixture modified by crumb rubber is uncertain specifically when it is added by the dry method due to the low stability and cracking performance of the produced mixtures. Moreover, the high air void content of the produced mixture results in its low resistance to moisture damage and aging effect. This study attempts to investigate the effect of moisture damage and aging on the cracking performance of rubberized asphalt mixtures. Indirect tensile strength test was used to investigate the CT index, fracture energy, and tensile strength. The IDEAL-CT characterization correlated well with field performance in terms of thermal cracking and reflective cracking. The test was conducted before and after exposure of the asphalt samples to two levels of aging and one level of moisture damage. Results show that the total fracture energy of rubberized asphalt is higher than that of the control mixtures. However, the rubberized mixture shows low tensile strength particularly for the moisture conditioning. Meanwhile, the rubberized mixture has a higher CT index value than the control mixtures.

1. Introduction

The increase in traffic loading reduces the service life of asphalt pavement and increases the maintenance and rehabilitation work. High cost of maintenance and rehabilitation of asphalt pavement introduces the need to use different materials for property enhancement of asphalt mixtures [1]. The use of waste materials is a promising step to improve the performance of asphalt mixture. Crumb rubber processed from the scrap tire is a widely used waste material that is produced in large volume due to the increased number of vehicles; specifically, more than 30,000 tons of scrap tires are produced each day in Malaysia, and only 5% of it are reused [2]. The large quantity of cumulative scrap tires becomes a serious problem that threatens the health and environment. Thus, many researchers have investigated the feasibility of using crumb rubber to modify asphalt mixture. Adding crumb rubber to asphalt mixture can enhance the properties of produced mixtures [3–6]. Crumb rubber can also improve the cracking resistance, rutting, and flexibility of asphalt mixture [8–10]. Two methods, namely, the dry and wet methods, can be used to incorporate crumb rubber in asphalt mixture. The dry method includes adding the crumb rubber as a replacement by weight of aggregate and mixing before compaction [10], while the wet method includes adding the crumb rubber to the asphalt binder as a modifier and then adding the aggregate. In the wet method, modifying the asphalt can effectively improve the performance of the asphalt mixture due to the interaction of the crumb rubber particles and the asphalt binder. However, Moreno [8] declared that modifying the asphalt mixture using the dry process can improve the stiffness but can decrease the tensile strength and adhesion. Other studies conducted by Moreno and Rahman [11–13] showed undesirable effect of crumb rubber on the asphalt mixture; specifically, the crumb rubber increases the sensitivity of asphalt mixture to moisture damage due to the poor interaction between the crumb rubber and the asphalt binder. Thus, further investigations are needed to clarify the effect of crumb rubber on the asphalt mixture. The current study used 1% crumb rubber content as recommended by previous studies [11,12] to investigate the moisture damage and aging of the produced asphalt mixtures. The indirect tensile asphalt

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cracking test (IDEAL-CT), the fracture energy at maximum load and total fracture energy, and the tensile strength were measured to evaluate the cracking performance of the modified asphalt mixture. The IDEAL-CT test showed promising results as it correlates to the resistance of the materials to crack propagation [13,14].

2. Materials

2.1. Asphalt and aggregates

60–70 PEN asphalt binder was used to produce the conventional hot mixture asphalt. The chemical and physical properties of asphalt are shown in Table 1. Aggregate particles were collected from the local quarry in Malaysia. The aggregate was sieved and batched in accordance to the Malaysian Public Works Department specification, and the hydrated lime was used at 2% to increase the moisture resistance of the asphalt mixtures. Detailed aggregate gradation of AC14 mix is shown in Table 2.

2.2. Crumb rubber

The size of the crumb rubber used in this study was retained at 1.18 mm sieve. The crumb rubber particles size range between 1.18 mm and 3.35 mm. The crumb rubber was mechanically shredded at ambient temperature from truck and car tires. The dry process method was used to incorporate crumb rubber into the aggregate prior to mixing with asphalt binder. A total of 1% by the weight of aggregate was added to the mixture using the dry process method. This amount was selected on the basis of the recommended content by the previous studies [11,12]. Table 3 shows the combined aggregate gradation of crumb rubber and aggregate.

2.3. Mixture preparation

Two mixture types, namely, control or the conventional mixture and the crumb rubber modified asphalt mixture, were compared in this study. Both mixtures were prepared using the Marshall mix design method. The rubberized asphalt mixture was prepared by replacing 1% of the weight of aggregate retained on sieve size of 1.18 mm with shredded crumb rubber. In the laboratory, the aggregate, binder, and crumb rubber were mixed and compacted at 160 ± 5 °C. The mixtures were compacted with 75 blows on each side with the standard Marshall hammer to avoid the disintegration of materials. After compaction, the samples were removed from the molds and allowed to cool at room temperature (Fig. 1). 8 types of asphalt blends were prepared in this study as shown in Table 4.

3. Test method

The study can be divided into two phases. In the first phase, mixture preparation includes two asphalt mixtures; a control mix and a rubberized modified asphalt mixture prepared with a dry process. The second phase includes determining the volumetric properties of the obtained mixtures. After volumetric evaluation of samples, the samples were aged and moisture conditioned. The indirect tensile cracking test was conducted to investigate the impact of long-term aging and moisture conditioning on the cracking properties of the rubberized asphalt mixtures. To fully understand the fracture properties of the rubberized mixtures, a total of three variables were evaluated in this study; the tensile load, CT-Index, and fracture energy.

Table 2
Aggregate gradation and size.

Sieve Size (mm)	Specification (percent passing, %)	Average Passing (%)	Average Retained (%)
20	100	100	0
14	90–100	95	5
10	76–86	81	14
5	50–62	56	25
3.35	40–54	47	9
1.18	18–34	26	21
0.425	12–24	18	8
0.15	14–6	10	8
0.075	4–8	6	4
Filler 6		–	6

3.1. Stability and volumetric properties

All the volumetric properties were determined to calculate the optimum binder content of the mixtures according to the Marshall procedure specified by the JKR (2008) specification [15]. The compacted samples were then weighed in dry and underwater to determine the density according to ASTM D 2726 [16], and the maximum theoretical density was determined for the loose mixtures according to ASTM D2041 / D2041M-11 [17]. The compacted samples were then conditioned for 45 min at 60 °C to determine the stability and flow values by using Marshall stability test in accordance to ASTM D 1559 [18]. The volumetric properties of the control and modified mixtures are shown in Table 5.

3.2. Moisture conditioning

Moisture damage includes partial saturation by introducing the sample to vacuumed pressure of 30 mm HQ absolute pressure for 5 min. Then, the sample was submerged in the water for 24 h at 60 °C. The moisture conditioning was performed according to D4867M 2014 [19]. Thereafter, the samples were placed into a water bath of 20 °C for 2 h before conducting the test.

3.3. Aging conditioning

Two stages of aging were conducted as in the AASHTO R30 standard procedure [20], namely, the short-term aging (STA) and long-term aging (LTA) , were applied to the produced asphalt mixtures. The STA includes placing the loose asphalt mixture before compaction in the oven for 2 h at 145 °C, and the mixture was stirred at every 1 h to ensure homogenous distribution of the heating in

Table 1
Properties of 60–70 penetration grade asphalt binder.

Asphalt Properties	Unit	Specification	Results	Method
Penetration at 25 °C	dmm	60–70	66.7	ASTM D5
Softening Point	°C	47 Min	48	ASTM D36
Ductility	cm	greater than 100	137	ASTM D113
Specific Gravity	–	–	1.033	ASTM D70
Viscosity at 135 °C	Pa•s	–	0.4	ASTM D4402/D4402M
Viscosity at 165 °C	Pa•s	–	0.2	ASTM D4402/D4402M

Table 3
Aggregate gradation combination with crumb rubber.

Sieve Size (mm)	Specification (percent passing, %)	Average passing, (%)	Average retained (%)	Combined rubber asphalt mixtures (percent retained, %)
20	100	100	0	0
14	90–100	95	5	5
10	76–86	81	14	14
5	50–62	56	25	25
3.35	40–54	47	9	9
2.65	–	–	–	**0.3**
2.0	–	–	–	**0.5**
1.7	–	–	–	**0.2**
1.18	18–34	26	21	20
0.425	12–24	18	8	8
0.15	14–6	10	8	8
0.075	4–8	6	4	4
Filler		6	6	6

Fig 1. Materials and samples of asphalt mixtures.

Table 4
Asphalt mixture type coding.

Mixture Coding	Description
CON	Control Mixture
CON-STA	Control Short-Term Aging Mixture
CON-LA	Control Long-Term Aging
CON-MD	Control Moisture Damage
RU	Rubber Mixture
RU-STA	Rubber Short-Term Aging Mixture
RU-LA	Rubber Long-Term Aging
RU-MD	Rubber Moisture Damage

Table 5
Results of Marshall mix design.

Description	Control Asphalt Mixture	Rubberized Asphalt Mixture (1% rubber)
Void filled with binder (%)	79.9	76
Bulk density (kg/m^3)	2360	2340
Flow (mm)	2.71	3.48
Air void (%)	2.91	3.5
Stability (N)	16,410	12,930
Stiffness (N/mm)	6055	3715
Asphalt binder content (%)	5	5.3

the asphalt mixture. For the LTA, the process includes placing the sample in the oven for 120 h at 85 °C.

3.4. Indirect tensile cracking test (IDEAL-CT)

IDEAL-CT was conducted to evaluate the cracking propagation rate of the control and rubberized asphalt mixtures. The IDEAL-CT developed by Zhou [13] was performed using similar procedures to the traditional indirect tensile strength test. All the control and rubberized asphalt samples were prepared within 7 ± 0.5% air void content. This test was conducted with a constant displacement rate of 50 mm/min at 25 °C. The CT index is the parameter used in the IDEAL-CT to evaluate the cracking resistance of asphalt mixtures. The good correlation of CT index with field cracking performance was further confirmed by the cracking sections constructed at the test track of the National Center for Asphalt Technology. The CT index has been proposed to determine the crack propagation rate of the asphalt mixtures as a simple and valuable index. The CT index can be calculated using Eq. (1).

$$\mathrm{CTindix} = \frac{G_f}{|m_{75}|} \times \frac{I_{75}}{D} \quad (1)$$

where G_f is the fracture energy (J/m^2), I_{75} is the displacement at the 75% point of the peak load (mm), and D is the diameter of the sample (mm). $|m_{75}|$ is the absolute value of the slope at the 75% inflection point of the peak load (kN/mm).

3.5. Fracture energy

Fracture energy at maximum displacement and total fracture energy were defined to determine the cracking resistance of the control and rubberized asphalt mixtures. The energy at max load represents the area under the load–displacement curve before the failure point, while the total fracture energy represents the total area under the load–displacement curve, as shown in Fig. 2.

According to RILEM TC 50-FMC [21], the fracture energy G_f is calculated using Eq. (2).

$$G_f = \frac{W_f}{A_f} \quad (2)$$

whereG_f = fracture energy (J/m^2), andW_f = work of fracture (J),A_f =-fracture area (m^2)

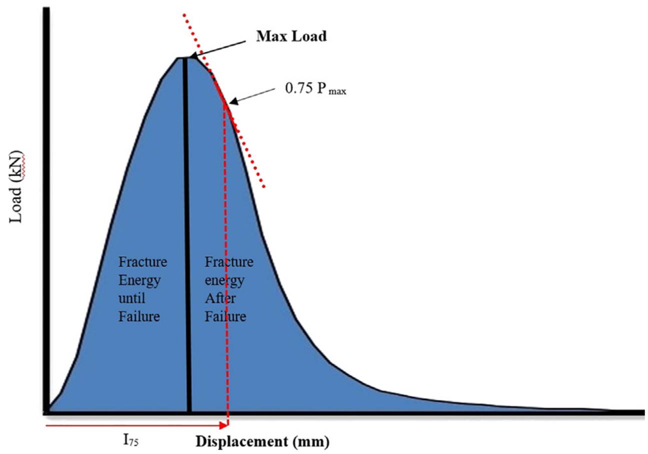

Fig 2. Typical load–displacement curve showing fracture energy [13].

3.6. Indirect tensile strength test

The ITS test was performed in accordance with ASTM D6931-12 [22]. The indirect tensile test was used to calculate the tensile strength of the conditioned and unconditioned sample. The load was applied at a constant displacement rate of 50 mm/min until the maximum load was reached. The tensile strength along the diametrical axes of the sample was calculated using Eq. (2).

$$S_t = \frac{2000P}{\pi D t} \quad (3)$$

where St is the indirect tensile strength (kPa); P is the peak load (N); D and t are the diameter and height of the sample (mm), respectively. Moreover, the tensile strength after conditioning the sample was calculated to evaluate the effect of moisture and aging conditioning on the tensile strength of asphalt mixtures.

4. Results and discussion

4.1. Fracture energy

The typical plot of the load–displacement curve for both mixtures at different conditioning types is shown in Fig. 3. The load–displacement plot shows that the control asphalt mixture has higher peak load and smaller deformation than the rubberized asphalt mixture.

The fracture energy, fracture energy at maximum displacement, and the maximum displacement at peak loads of the control and rubberized asphalt mixtures are shown in Fig. 4. The fracture energy results show that the control asphalt mixture performs better before and after conditioning than the rubberized asphalt mixture. The fracture energy results at the maximum load for all rubberized asphalt mixtures are slightly lower than those for the control mixtures. Meanwhile, the total fracture energy of RU mixture is higher than that of the C mixture. However, the effect of aging and moisture damage on the rubberized asphalt mixture is greater than that on the control mixture even though the two mixtures have the same trend. The total fracture energy of RU-STA mixture shows improvement in the fracture energy compared with that of the RU mixture before conditioning. This finding is comparable to that of a previous researcher who declared the importance of STA (digestion time) in increasing the performance of rubberized asphalt mixtures [11]. However, the fracture energy of RU-MD mixture is the lowest, which confirms the finding obtained by Moreno [7], who observed decrement in the indirect tensile and adhesive force with the rubber addition. The undesirable effect of moisture damage may relate to the high air void content of the rubberized asphalt mixtures. This condition allows for more water to penetrate inside the mixture, which consequently causes more oxidation for the asphalt film coating.

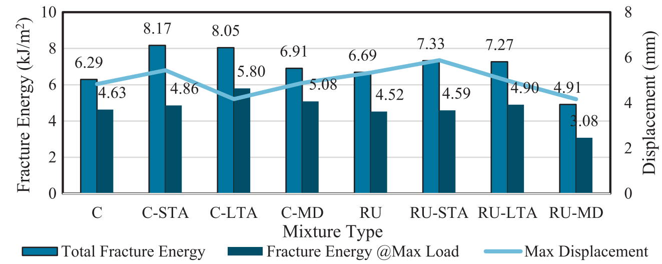

Fig 4. Fracture energy at max load, total fracture energy, and max displacement at max load.

The maximum displacement at the peak load of the control asphalt mixture is lower than that of the rubber mixtures in general. This finding demonstrates the ductile behavior of the rubberized asphalt mixtures due to the presence of rubber particles [12]. Meanwhile, the moisture damage of the rubberized asphalt mixture significantly reduces the maximum displacement compared with that of the control mixture.

4.2. Ideal CT

The CT index results from the cracking test are shown in Fig. 5. The results show that rubberized asphalt mixture has better resistance against crack propagation than the control asphalt mixtures. However, the control mixture has higher fracture energy because the CT index represents the behavior of materials at a point located in the post-failure zone in the load–displacement curve. The CT index of the rubberized asphalt mixture shows enhanced perfor-

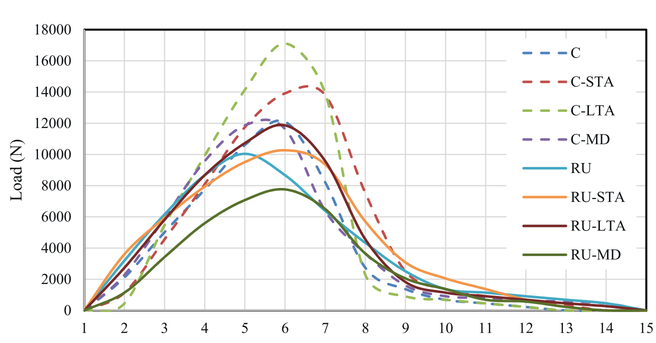

Fig 3. Load–displacement curves for the control and rubberized asphalt mixtures.

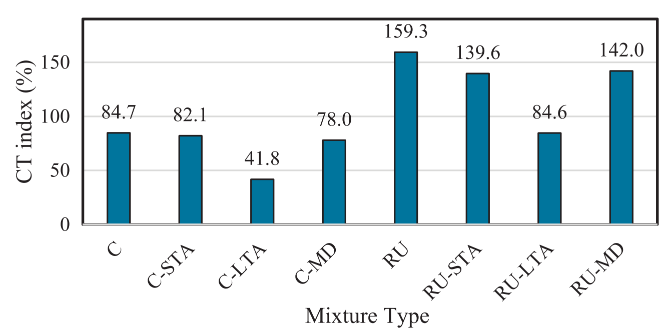

Fig 5. CT Index of the control and rubberized asphalt mixtures.

mance compared with that of the control mixtures. The rubber increases the CT index of the asphalt mixtures by 100%, 75%, and 100%, and 83% for C, C-STA, C-LTA, and C-MD, respectively. The CT index of the aged rubberized mixture decreases by 14% and 45% for the STA and LTA, respectively. Meanwhile, the moisture damage negatively affects the CT index of the rubberized mixture, and the RU-MD displaces lower CT index value than the RU mixtures by 25%. The results show that the CT index values are very sensitive to the aging condition. However, the CT index can also be an indicator of flexibility of materials; it is similar to the flexibility index parameter obtained by the semi-circle bending test [23]. Both parameters consider the slope of the load–displacement curve for normalizing the fracture energy. High CT-Index of rubberized mixtures is related to the post peak load behavior of the mixture's load–displacement curve. Note that with the initiation of macro-crack, maximum load capacity of any asphalt mixtures will significantly decrease. In case of the rubberized mixture, the loads measured after the peak load gradually reduce to failure as seen in the load–displacement curve resulted in high energy consumed compared to the sudden failure experienced by the control mixture. Generally, the larger the fracture energy, the better the cracking resistance of asphalt mixtures. The harder the mixture, the faster the cracks propagate, the higher |m75|, and consequently the poorer the crack resistance. It is obvious that rubberized mixture has higher fracture energy as in section 4.1, thus is showed high resistance to crack propagation.

4.3. Indirect tensile strength

Fig. 6 illustrates the tensile strength of the control and rubberized asphalt mixtures. The result of tensile strength of the control mixtures is higher than that of the rubberized asphalt mixture. Low tensile strength of rubberized asphalt mixture is due to the minor expansion of the rubberized sample after being extruded from the mold due to the rubber particles swelling effect. The expansion can generate cracks and voids within the mixture's matrix leading to weak bonding properties for the produced mixtures. Aging conditioning of the control mixtures increases the tensile strength by 12% and 26% for C-STA and C-LTA, respectively. Meanwhile, the moisture damage slightly decreases the tensile strength by 8%. The rubberized asphalt mixtures show a different trend, that is, the tensile strength increases slightly for the RU-STA and remains the same for RU-LTA. This result indicates that LTA can increase the adhesion force of the control mixture but can decrease the adhesion of the rubberized mixtures. This finding may be due to the expansion of rubber particles after heating the sample, which may lead to the development of the cracks in the rubberized mixtures (Fig. 7). The moisture conditioning of the rubberized asphalt decreases the tensile strength by 23%. This result is in agreement with the findings by the authors in [11,13], who showed high moisture susceptibility of mixture modified with crumb rubber.

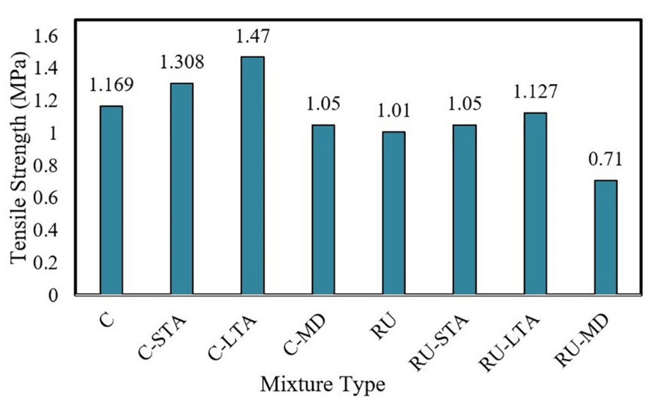

Fig 6. Tensile strength of the control and rubberized asphalt mixtures.

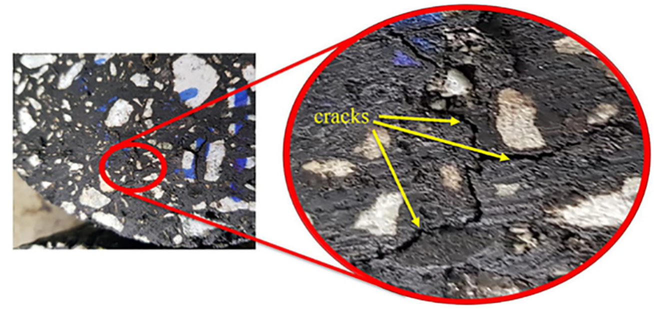

Fig 7. Cracking on rubberized asphalt sample after LTA.

The high moisture susceptibility of the rubberized mixture is because the crumb rubber produces additional voids in the mixture and causes weak interfacial transition zones, ITZ leading to less resistance against moisture damage following deformation. High air void content can lead to water penetration into the macro pores and peel off the binder film coating on the aggregate surface. Fig. 8 displays the weak ITZ areas (yellow arrows) due to the effect of moisture conditioning on the fracture surface of the rubberized and control mixtures. The figure indicates that the binder film on the aggregate surface is significantly removed due to water diffusion into the sample.

5. Conclusions

From the evaluation, the conclusions are obtained and summarized as follows:

i. The rubberized asphalt mixture has lower fracture energy at the maximum load. In fact, fracture energy at the peak load is attributed to the energy consumed for the crack initiation while energy after the peak load represented the crack propagation stage. As a result, the rubberized mixture consumes lower energy in the crack initiation stage while consumes high energy at the crack propagation stage.
ii. The STA increases the fracture energy and tensile strength of rubberized asphalt mixture. In contrast, the LTA decreases the fracture energy and tensile strength. It can be concluded that, by aging the rubberized mixtures in the loose form enhances the cracking resistance. On the contrary, LTA can cause potential degradation of the compacted rubberized sample.
iii. The moisture conditioning significantly decreases the fracture energy and tensile strength of the rubberized asphalt mixture. The moisture impact on the rubberized mixture could be due to the extra air void generated after the sample's extraction and rubber swelling due to heating.
iv. The CT index of the rubberized asphalt mixture is higher than that of the control mixture. Therefore, the resistance of rubberized asphalt mixture to crack propagation is higher than that of the control mixture. The CT-Index is a useful parameter to investigate the behavior of the material after the crack initiation and propagation (the post peak load of the load–displacement curve).

Further research is needed to investigate the potential of using crumb rubber to increase the porosity of the produced asphalt mixtures by using micro-computed tomography (CT-SCAN). CT-SCAN

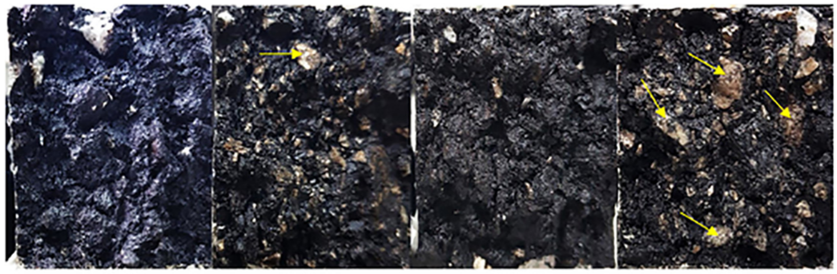

Fig 8. Fracture surface of the conditioned and unconditioned samples for the control and rubberized mixtures after testing.

uses computer processing to create cross-sectional images (slices) of the tested sample and provide 3D microscopy images for describing the changes in rubberized mixture under moisture and aging conditioning particularly on the air voids distribution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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