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# Fracture resistance of asphalt mixtures under mixed-mode I/II loading at low-temperature: Without and with nano $SiO_2$

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## HIGHLIGHTS

- The addition of 1.2% Nano-Silica improves the fracture resistance of asphalt mixtures.
- As the temperature decreases, the critical SIFs of asphalt mixtures increases.
- By adding Nano-$SiO_2$, the fracture resistance of the HMA mixtures increased for all the loading modes.
- The maximum value of critical SIFs in both modified and unmodified asphalt mixtures was related to pure mode I ($M^e$ = 1).
- The critical SIF of pure mode II asphalt mixtures with vertical cracks is higher than angular cracks.

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## ABSTRACT

Increasing traffic congestion especially in cold climates has increased the damage caused by low-temperature cracks (LTCs) in the asphalt mix where the constituents are not able to withstand the loads required in these climates lonely and using the modifier is undeniable. In recent years, some research fields have been conducted on the use of nanomaterials as a modifier in asphalt mixtures to improve their properties. In accordance with previous researches, one of the nanomaterials that have appropriate effects on the performance of asphalt mixtures is Nano-$SiO_2$. In this study, the effect of Nano-$SiO_2$ on the incident of low-temperature cracks in asphalt mixtures is experimentally investigated. For this purpose, the semicircular bending test (SCB) under mixed-mode I/II loading is used for investigating the effect of Nano-$SiO_2$ on forming cracks in asphalt (i.e., vertical and angular crack) at different temperatures of −5 ℃, −15 ℃, and −25 ℃. Results show that the maximum stress intensity factor (SIF) of the modified asphalt mixtures is related to specimens which have angular crack under pure opening mode, while the maximum critical SIF is improved when Nano-$SiO_2$ is added to specimens which have vertical cracks under mixed-mode I/II with $M^e$ = 0.6 at −25 ℃. Furthermore, the critical SIF of all specimens having both vertical and angular cracks is significantly improved by adding 1.2% of Nano-$SiO_2$ at all temperatures.

## 1. Introduction

The behavior of asphalt mixture depends on the behavior of asphalt binder. Asphalt binder has visco-elastic behavior, therefore the behavior of asphalt mixtures changes with temperature change. The asphalt binder shows visco elasto-plastic behaviour and elastic behaviour at high and low temperatures, respectively. High temperatures causes failure mode such as rutting that it more occurs along wheel-path. Conversely low temperatures causes thermal cracking and acceleration of the fatigue cracking propagation of the asphalt mixture under traffic load.

The most important pavement cracks caused by cold climates are low-temperature cracks (LTCs) that are spreading day by day due to the passing of vehicles. Creation and expansion of LTCs necessitates early and premature repairs. Therefore, use of modified asphalt mixtures is a suitable solution for preventing LTCs occurrence in cold regions. The LTCs is more prevalent in cold climates with low temperatures, where the asphalt pavement behaves like a brittle and elastic material. Research on the creation and expansion of LTCs due to environmental conditions as well as the crossing of traffic loads is evaluated under fracture mechanics science. Majidzade et al. [1], as well as Molenaar et al. [2], used the science of fracture mechanics to investigate the crack of asphalt mixtures for the first time. Because of the occurrence of LTCs at low temperatures and the brittle behavior of asphalt mixtures at these temperatures, the principles of linear elastic fracture

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mechanics (LEFM) presented by Griffiths can be used to study LTCs [3]. Parameters that affect the growth of cracks in asphalt mixtures include the type of admixture for binder modification, the percentage of asphalt mixture void, temperature variations, and loading mode [4].

## 2. Literature review

Based on previous researches, Nanomaterials are one of the useful modifiers to improve the properties of asphalt mixtures. Rouyu Li et al. [5], conducted a review study to investigate the application and impact of different types of nanoparticles on asphalt materials. According to their studies, the addition of Nano-$SiO_2$, Nano-$TiO_2$, Nano-ZnO, and Nano-$CaCO_3$ to asphalt mixtures significantly increases the resistance to low-temperature crack and also improves the performance of high-temperature asphalt mixtures. According to studies by Ashish et al. [6], the most important nanomaterials that improve the rheological and mechanical properties of binder in asphalt mixtures include OMNC, CNT, $SiO_2$, $TiO_2$, and ZnO.

The binder modification with Nano-$SiO_2$ results in increased viscosity, increased softening point, reduced ductility, and increased elastic modulus [7–10]. Application of binder modified with Nano-$SiO_2$ in asphalt mixtures improves some of their properties such as improved dynamic and psychological modulus [11], increased Marshall resistance [12], increased modulus of hardness and less susceptibility to temperature changes [13]. Based on laboratory work by researchers over the years, it has been found that asphalt mixtures modified with Nano-$SiO_2$ have a longer fatigue life [7,14,15], greater rutting resistance and less rut depth [14,16], increased resistance to permanent deformation [17], increased anti-aging properties through delayed oxidation [18], increased resistance to moisture damage [18,19], increased anti-stripping property [15] and reduced creep strain deformation [15,20]. Furthermore, the simultaneous incorporation of Nano-$SiO_2$ and SBS improves the self-healing properties of asphalt mixtures [21].

Aliha et al. [22], investigated the fracture toughness of Mode I asphalt mixtures modified with SBS, CR, Nanoclay, Nanosilica, and Lucobit using two types of circular test specimens (ENDB and ENDC). The results showed that all modifiers increased the fracture toughness of HMA mixtures. Fallah Tafti and Hoseini Aqda [23], estimated the fracture toughness of Mode I modified asphalt mixtures with five modifiers including Elastoplastomer Polymer Strings (EPS), Parafiber, Sulfur Polymer, Polyolefin-Aramid Compound Structural Fibers (PACSF), and Sasobit at 15℃. The results showed that all modifiers except EPS increased the fracture toughness of Mode I and the fracture toughness increased as the amount of modifier increased. Pirmohammad et al. [24,25], investigated the fracture strength of asphalt mixtures modified with Nano-$Fe_2O_3$, CNTs, and Nanoclay reference under mixed-mode I/II by using SCB test at −15℃ and showed that the modified specimens showed better fracture strength. On the other hand, the fracture strength of CNTs modified asphalt mixtures is higher. Pirmohammad and Shabani [26], investigated the critical stress intensity factor of three types of HMA (i.e. asphalt mixture modified with CR and SBS additives and an unmodified asphalt mixture) using SCB under mixed-mode I/II loading. They observed that the additives CR and SBS increased the fracture resistance of the asphalt mixture, however, the SBS mixture showed higher fracture resistance. The results also showed that HMA is not in critical conditions under pure Mode I loading and is in critical conditions under mixed-mode I/II loading. Ziari et al. [27], used glass fiber additive in asphalt mixtures modified with different percentages of RAP to improve the negative effects of RAP on asphalt mixtures and to investigate their fracture resistance at −15℃ under opening mode loading conditions. The results showed that using the glass fibers improves the fracture performance of these mixtures. Hong et al. [28], investigated the fracture resistance of asphalt mixtures containing coal gangue powder and polyester fibers using the SCB test. The results of experiments showed that crack resistance increased with decreasing temperature. Pirmohammad et al. [29,30], studied the effect of fibers (kenaf, goat wool, and carbon) on fracture resistance of HMA. They used the SCB test under mixed-mode I/II loading at −15℃. Their results indicated that kenaf, goat wool, and carbon fibers increased fracture resistance which this increase was dependent on fiber length. Pirmohammad et al. [31], evaluated effect of basalt fibres (with three different contents and lengths) on fracture toughness of asphalt mixture by using SCB under under Pure mode I, pure mode II and mixed mode I/II loading and analysis of ANOVA. The results showed that the use of fiber content increased the fracture resistance and the reinforced asphalt mixture by 0.3% of basalt fibres with the length of 4 mm shows the highest fracture toughness. Analysis of ANOVA showed that and mode of loading, length of basalt fibre, and content of basalt fibre have significant influence on the fracture toughness of asphalt mixtures.

According to the previous studies on the critical SIF of modified asphalt mixtures, there isn't a study that evaluates the effect of $SiO_2$ nanoparticles on the critical SIF of asphalt mixtures. Since in [14,32] the researchers of the present study have investigated the effect of Nano-Silica additive on binder and asphalt mix behavior against rutting and fatigue failure, however, it is necessary to investigate the effect of optimum Nano-Silica percent (i.e., 1.2%) on fracture resistance of the asphalt mixtures in this paper. The main objective of the present study is to evaluate the effect of adding 1.2% Nano-Silica as the optimum percentage on the critical SIF of asphalt mixtures, For this purpose, the SCB is used in three sub-zero temperature conditions (-5℃, −15℃, and −25℃) and in opening-shearing mixed-mode (I/II) loading. Furthermore, in this study, the effect of the geometrical shape of the crack under the mentioned conditions is investigated, so that SCB specimens are prepared with two types of vertical and angular cracks.

## 3. Experimental

### 3.1. Materials

The aggregate materials used in this study are including limestone aggregate type and their gradation size is according to the Iran Highway Asphalt Paving Code Number (Code 234) with a maximum nominal aggregate size of 19 mm for Topeka layer. The reason for choosing this type of aggregate is the better fracture resistance than other aggregate materials [33]. Table 1 shows the aggregate gradation used in this study. The aggregate gradation procedure tests were performed according to AASHTO-T27 standard. Table 2 shows the physical properties of these limestone aggregates. The filler used in this study is also limestone powder.

**Table 1**
Aggregate gradation used in this study.

| Sieve size (mm) | Gradation limits | Value |
|---|---|---|
| 19 | 100 | 100 |
| 12.5 | 90–100 | 93.3 |
| 4.75 | 44–74 | 46.8 |
| 2.36 | 28–58 | 34.5 |
| 0.3 | 5–21 | 10.5 |
| 0.075 | 2–10 | 4.3 |

**Table 2**
Physical properties of limestone aggregate used in this study.

| Physical properties | Test method | | Code 234 Limitation | | Result |
|---|---|---|---|---|---|
| | ASTM | AASHTO | Top coat | Binder | |
| Gravity Los Angeles abrasion (%) | C131 | T96 | 30 | 40 | 21.6 |
| Percent fracture (two faces) (%) | D5821 | – | 90 | 80 | 93 |
| Water absorption (Coarse aggregate) (%) | – | T85 | 2.5 | 2.5 | 1.2 |
| Absorption (fine aggregate) | – | T84 | 2.5 | 2.8 | 2.3 |

**Table 3**
Specifications of the used binder in this study.

| Property | ASTM Standard | Value |
|---|---|---|
| Specific gravity at 25 °C (g/cm3) | D70 | 1.013 |
| Flash point (°C) | D99 | 308 |
| Penetration at 25 °C (0.1 mm) | D5 | 68 |
| Ductility at 25 °C (cm) | D113 | 102 |
| Softening point (°C) | D36 | 50 |
| Loss of weight | – | 0.2 |
| Degree of purity | – | 99.6 |
| Performance grade (PG) | – | 64-22 |

The used binder in this study is 60/70 binder (equivalent to binder PG64-22). Table 3 provides complete specifications of used binder.

The nanomaterials used in this research is silicon dioxide, a withe crystalline material with $SiO_2$ chemical formula. The most important advantage of Nano-Silica is its lower production cost than other nanomaterials as well as higher performance properties [34]. The optimum percentage of Nano-Silica was also selected based on past research and also considering economic issues equal to 1.2% of the binder weight [14,32]. Table 4 presents characteristics of the Nano-$SiO_2$ used in this study.

Also, the solvent used in this study was kerosine, which was used to disperse the nanoparticles in the binder and its properties are shown in Table 5.

### 3.2. Specimen preparation

To prepare asphalt mixtures modified with Nano-$SiO_2$, the binder and nanoparticle must firstly be combined. For this purpose, there are two common mixing methods, wet and dry [14]. In this study, for mixing Nano-Silica and binder to achieve a homogeneous mix, in a more sophisticated way, the Nano-$SiO_2$ was firstly dispersed in the kerosine solvent by high shear mixer for 30 min with 2500 rpm. Then, for final mixing, the binder was warmed to 150℃ and stir for half an hour, at identical intervals, slowly mixing the nanoparticle-solvent in the mixer and continuing the mixing process at 4000 rpm until a homogeneous mixture of binder and nanoparticles was obtained. The Marshall method according to ASTM D1559 standard was used to determine the optimum binder content of asphalt mixes.

To prepare the asphalt mixture with base and modified binder, the materials and the binder were firstly heated in an oven at 156-152℃ for 16 h. Then, the binder was added to the aggregates at the optimum percentage (5% for the base specimen and 6% for the Nano-$SiO_2$ modified specimen) and poured into a cylindrical mold with a diameter of 150 mm and a height of 120 mm. Cultivation was carried out at 143-146℃.

### 3.3. Methodology

#### 3.3.1. Preparation of SCB specimen

The SCB test is particularly popular because of its many advantages, such as reproducibility, easy to prepare specimens, reliable results, sensitivity to parameters of asphalt mixture, appropriate loading pattern and close to actual loading conditions and coefficient of variation of less than 15% of the specimens [35]. For the preparation of SCB specimens, the cylindrical specimens were firstly cut into circular discs with a thickness of 30 mm using a rotary disc cutter. Then they were cut in half with the thickest blade. Next, the cracks were created vertically and angularly at an angle $\alpha$, relative to the central axis of the plate, 22.5 mm in length, using a waterjet device. The SCB specimens of this study were 75 mm in radius and 30 mm in thickness. Due to the created crack length, $a$ and the radius of the SCB specimens, $R$, the ratio of $a/R$ in the specimens is approximately 0.3.

#### 3.3.2. Fracture theory and testing

To obtain SCB specimens to the desired temperature conditions (temperatures of −5 ℃, −15 ℃, and −25 ℃) they were placed in freezers with the same temperatures for at least 4 h. After the SCB specimens reached these temperatures, they were taken from the freezer and were placed in the SCB test apparatus one by one. Fig. 1 shows the SCB test machine, samples of SCB specimens after fracture tests and supports of the SCB test machine. It should be noticed that the time interval between taking and testing the specimens was short enough so that the temperature variations were negligible. The loading rate was 1 mm/min, and the distance of the lower supports was adjusted according to each mode of loading. All steps of the SCB test were performed according to the requirements of AASHTO TP 105-13 [36].

According to Fig. 2, there are three methods to create a mixed-mode I/II loading: 1) moving one of the support rollers (see Fig. 2. (a)), 2) shifting the cracking position from the center axis of the specimen to the left or right (see Fig. 2. (b)), and 3) creating an angular crack relative to the center axis of the specimen (see Fig. 2. (c)). In this study, the first method was used for the specimens with vertical crack, and the first and third methods were simultaneously used for the specimens with angular crack. Moreover, to show the contribution of opening and shear loading modes, the mixity parameter, $M^e$ according to Eq. (1) is used [37]:

$$M^e = \frac{2}{\pi} tg^{-1}\left(\frac{K_I}{K_{II}}\right) \tag{1}$$

**Table 4**
Characteristics of Nano-$SiO_2$ used in this study.

| Water absorption (%) | Degree of purity (%) | Special surface area ($M^2$/g) | Morphology | Color | Particle size (Nm) | Bulk specific Gravity (g/cc) | Chemical formula |
|---|---|---|---|---|---|---|---|
| 0.2< | 99.9 | 160 | Spherical | White | 80 | 2.4 | SiO2 |

**Table 5**
Characteristics of the solvent (kerosine) used in Mixing binder and nanomaterial.

| Chemical formula | Flash point (℃) | Vaporizing point (℃) | Density ($gr/cm^3$) |
|---|---|---|---|
| C6 | 85 | 155 | 0.75 |

$K_I$ and $K_{II}$ are SIF of mode I and mode II loading, respectively. The value of $M^e$ for pure opening mode equals one, for pure shearing mode equals zero, and for mixed-mode opening-shearing loading is between zero and one. In this study, five $M^e$ were used ($M^e = 0$, $M^e = 0.2$, $M^e = 0.4$, $M^e = 0.6$, $M^e = 0.8$ and $M^e = 1.0$).

Using the critical load, the critical SIFs could be calculated for each $M^e$. Eqs (2) - (4) show the critical SIFs for mode I loading, mode II loading, and mixed-mode I/II loading, respectively [37].

$$K_{If} = Y_I \frac{P_{cr}}{2Rt}\sqrt{\pi a} \tag{2}$$

$$K_{IIf} = Y_{II} \frac{P_{cr}}{2Rt}\sqrt{\pi a} \tag{3}$$

$$K_{eff} = \sqrt{K_{If}^2 + K_{IIf}^2} \tag{4}$$

In these equations, $K_{If}$ and $K_{IIf}$ are critical SIFs of loading modes I and II, respectively, $K_{eff}$ is effective critical SIF, $R$ is the radius of SCB specimens equal to 75 mm, $t$ is the thickness of specimens equal to 30 mm, $a$ is the crack length and equal to 22.5 mm, and $P_{cr}$ is the critical load of the experiments. $Y_I$ and $Y_{II}$ are the geometry factors of mode I and II, respectively, which are corresponding values for the tested modes in this study for each $M^e$ in Table 6.

## 4. Results and discussions

As described in the previous sections, the SCB test was conducted on each specimen with three replicates to determine the fracture resistance of asphalt mixtures modified with Nano-$SiO_2$ under different mixed-modes open-shear loading at three different temperature conditions below zero (−5 ℃, −15 ℃, and −25 ℃). The purpose of this experiment is to obtain the critical failure load ($P_{cr}$) of the specimens. As it was seen from the fracture tests, the load increased linearly and then dropped at the onset of failure suddenly to zero. Hence, it can be concluded that the fracture of SCB specimens occurred according to the LEFM concept. Substituting the average values of $P_{cr}$ (obtained from fractures tests) and the values of $Y_I$ and $Y_{II}$ (given in Table 6) in Eqs. (2)-(4), the critical SIFs of modes I and II, and consequently the effective critical SIF could be obtained. The effect of adding Nano-$SiO_2$ on the critical SIF of asphalt mixtures is discussed below in detail.

### 4.1. Influence of Nano $SiO_2$

Fig. 3 show the effect of adding Nano-$SiO_2$ on the critical SIF of asphalt specimens modified with Nano-$SiO_2$ particles at three temperatures of −5℃, −15℃, and −25℃ for specimens containing vertical and angular cracks under different loading modes. According to these graphs, the addition of 1.2% Nano-Silica increases the critical SIF of asphalt mixtures at tested temperatures in both vertical

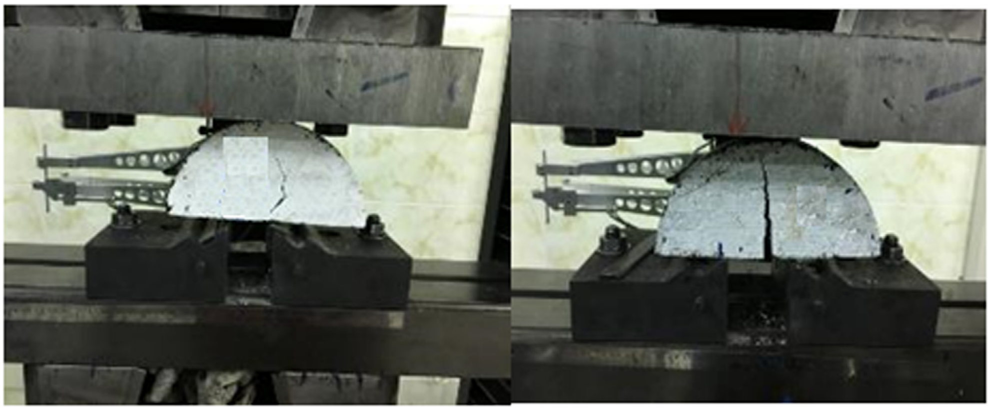
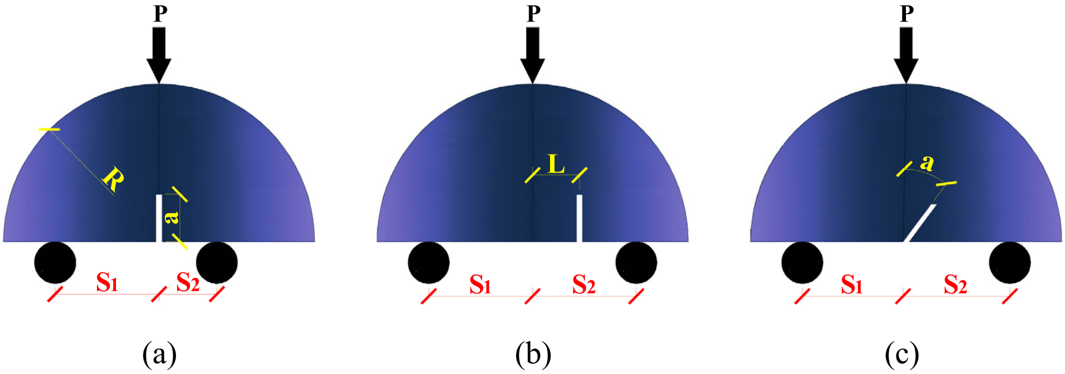


**Fig. 1.** The SCB test machine and samples of SCB specimens after fracture tests.



(a) (b) (c)

**Fig. 2.** Three methods to create a mixed-mode I/II loading.

**Table 6**
Value of the geometry factors $Y_I$ and $Y_{II}$ used in this study.

| Me | vertical crack | | angular crack | |
|---|---|---|---|---|
| | YI | YII | YI | YII |
| 0 | 0 | 1.42 | 0 | 0.82 |
| 0.2 | 0.36 | 1.06 | 0.18 | 0.84 |
| 0.4 | 0.6 | 0.83 | 0.55 | 0.85 |
| 0.6 | 0.86 | 0.62 | 1 | 0.77 |
| 0.8 | 1.19 | 0.38 | 1.5 | 0.49 |
| 1 | 1.71 | 0 | 1.71 | 0 |

and angular cracks. Additionally, the highest increase in critical SIF for specimens with vertical and angular cracks is 0.38 $MPa.m^{0.5}$ and 0.28 $MPa.m^{0.5}$, respectively, and the lowest increase is 0.1 $MPa.m^{0.5}$ and 0.08 $MPa.m^{0.5}$. According to these results, it can be found that the effect of adding Nano-$SiO_2$ to the specimens with vertical crack is greater than the specimens with angular crack. Generally it can be concluded that the use of Nano-$SiO_2$ has appropriate effects on the fracture resistance of asphalt mixtures, which is due to the increased adhesion between the binder and aggregates. Therefore, the SCB specimens prepared from asphalt mixtures modified by Nano-$SiO_2$ have a stronger adhesion factor than the SCB specimens prepared from base asphalt mixtures. In addition, the Nano-$SiO_2$ increases the stiffness, viscosity, and elastic behavior of the asphalt mixtures.

Based on the obtained results and the brittle behavior of the asphalt mixtures at temperatures below zero, it was seen that the addition of Nano-$SiO_2$ increases the brittle behavior of the asphalt mixtures and also exhibits more elastic behavior than the base specimens (without any additive), which increases the fracture resistance at temperatures below zero degrees centigrade.

Figs. 4 and 5 indicate the increase in critical SIF of asphalt mixtures modified by Nano-Silica with vertical and angular cracks, respectively. Based on these two diagrams, the ratio between the critical SIF of modified and unmodified specimens is more than one that shows the positive effect of using Nano-Silica. The maximum increase in critical SIF regarding vertical and angular cracks is 35% and 33%, respectively so that this maximum increase occurred in mixed-modes loading (i.e. critical loading), and the minimum increase is 11.9% and 5.7%, respectively. The average increase in critical SIF is due to the addition of Nano-Silica to all specimens is 22.5%. In addition, adding Nano-$SiO_2$ improved the SIF of mode II of asphalt mixtures more than the SIF of mode I. This indicates that the Nano-$SiO_2$ has improved the bonding between the aggregates in the shear planes.

### 4.2. Effect of different temperatures

Based on the results of the SCB experiment, the trend of changing the critical SIFs could be analyzed concerning temperature changes. For this purpose, Fig. 6-a and 6-b illustrate this trend at different temperatures with vertical and angular cracks, respectively.

According to Fig. 6-a in the vertical crack mode, for both the base and modified specimens, the value of critical SIFs increases with decreasing temperature and its changing trend follows a roughly similar pattern at all temperatures. Generally, the changing rate of critical SIF for modified specimens is greater than the base specimens when the temperature is decreased. The same trend is shown in Fig. 6-b for the specimens with angular crack. For the vertical crack state by adding 1.2% of Nano-Silica, the average increase in the critical SIFs of asphalt mixtures under mixed-mode I/II loading at −5℃, −15℃ and −25℃ is 18.67%, 21.31%, and 28.49%, respectively and likewise, for the angular crack state is 25.10%, 13.86%, and 15.62%, respectively. As can be seen, by adding 1.2% Nano-Silica, the highest critical SIF for the vertical and angular crack states is occurred at −25℃ and −5℃, respectively.

On the other hand, Fig. 6-a and 6-b show the changing rate of critical SIF from −5℃ to −25℃. According to these figures, the critical SIF when the temperature changes from −15℃ to −25℃ is greater than that of the temperature changes from −5℃ to −15℃. In mixed-mode loading these changes are more evident. With decreasing the temperature from −15℃ to −25℃, the rate of increasing the critical SIF for the modified asphalt mixtures with angular crack is more than the modified asphalt mixtures with vertical crack.

### 4.3. Influence of loading mode

Figs. 7 and 8 show critical SIFs of modified asphalt mixtures at temperatures of −5℃, −15℃ and, −25℃ for both vertical and angular cracks, respectively, which are under different loading conditions. According to these graphs, at all three temperatures in both crack states, the maximum critical SIF is related to the pure opening mode ($M^e$ = 1), in which this critical SIF greatly increases in the modified mixtures.

As shown in Fig. 7, the critical SIFs of base and modified specimens with vertical crack firstly decreases to its minimum value at $M^e$ = 0.4 or $M^e$ = 0.6 and then increases significantly. This indicates that the critical mode loading is related to the mixed-mode I/II loading. Additionally, the greatest effect of adding the Nano-$SiO_2$ on the fracture resistance the specimens with vertical crack is due to the mixed-mode I/II loading ($M^e$ = 0.6) which is equal to 35%.

Similarly, according to Fig. 8, the critical SIFs of base and modified specimens with angular crack firstly decreases to its minimum value at $M^e$ = 0.2 and then increases. This shows that the critical mode loading is related to the mixed-mode I/II loading. Additionally, the greatest effect of adding the Nano-$SiO_2$ on the fracture resistance of the specimens with angular crack is due to the mixed-mode I/II loading ($M^e$ = 0.4) which is equal to 33%.

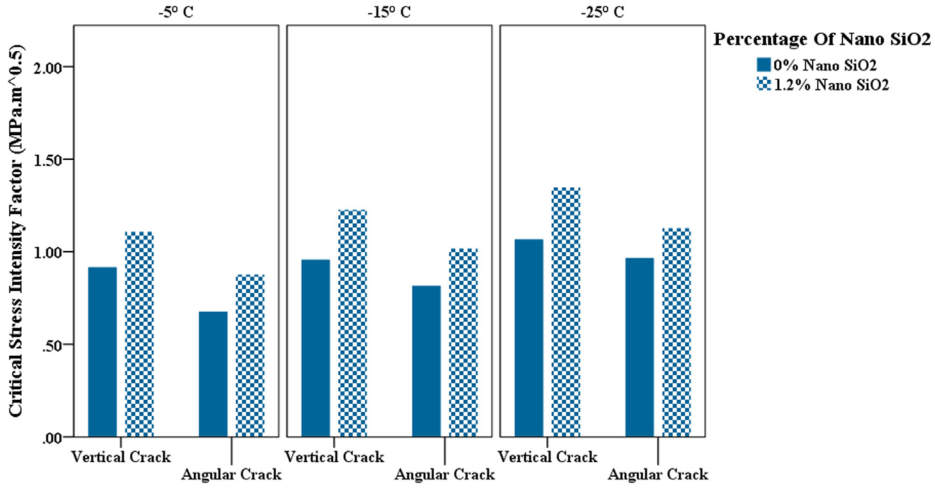
### 4.4. Influence of type of crack

Fig. 9 compares the effect of cracking type on the critical SIF of SCB specimens modified by 1.2% Nano-$SiO_2$. According to the results, in the pure mode II loading and the dominant mode II loading, the critical SIFs of the specimens with vertical crack is higher than the critical SIFs in the specimens with angular crack. As the value of $M^e$ increases, the critical SIFs of the specimens with angular crack increases, which this increasing will be more with decreasing the temperature. The maximum difference in critical SIF of the two crack types is 0.23 $MPa.m^{0.5}$ which is related to $M^e$ = 0.

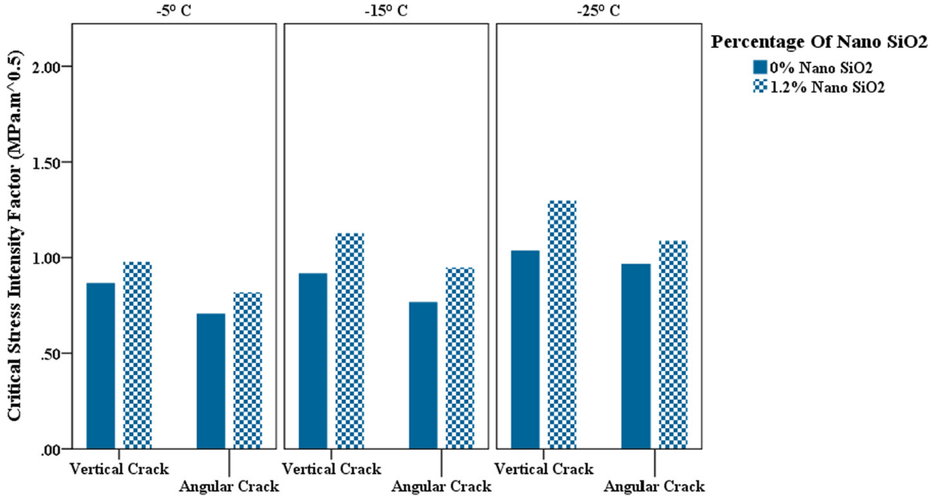
## 5. Summary and conclusion

Low-temperature crack is one of the most important cracks occurring in asphalt mixtures. The cold climate and increase in the number of vehicles could expand low-temperature cracks. In this study, the critical SIFs of asphalt mixtures modified with Nano-Silica was investigated by SCB test under mixed-mode I/II loading with The loading rate of 1 mm/min at temperatures of −5℃, −15℃, and −25℃ for specimens with vertical and angular cracks. The main results of this research study are as follows:

**(a) Me=0.0**



**(b) Me=0.2**



**(c) Me=0.4**

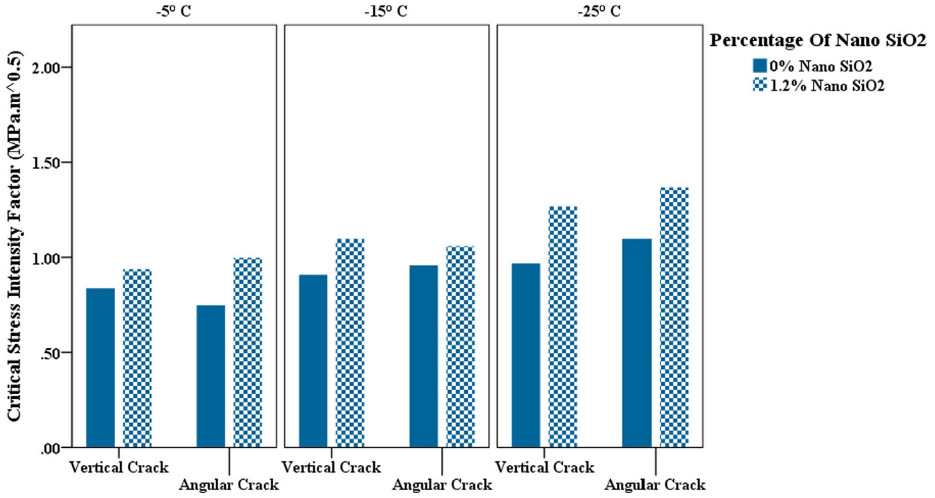
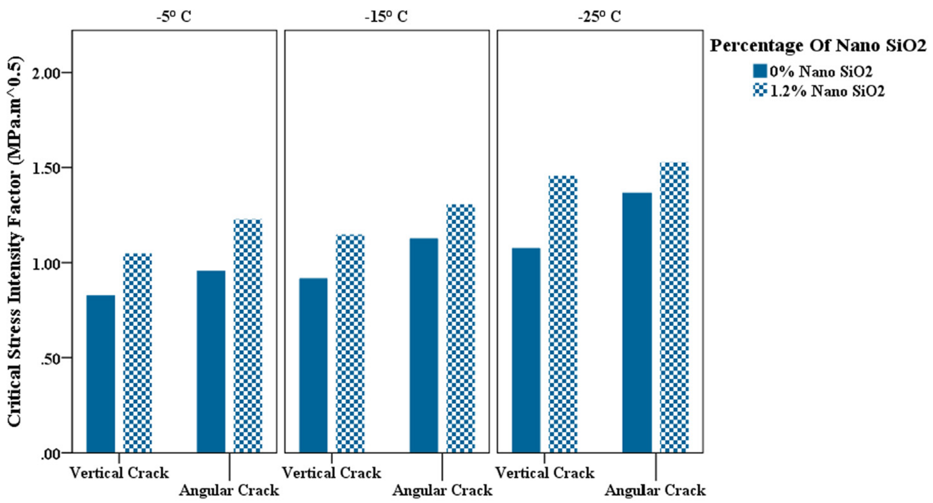
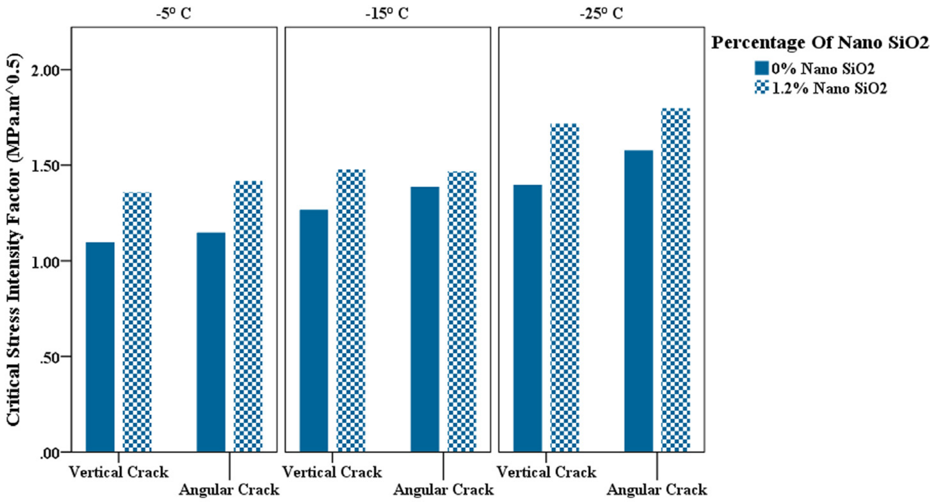


**Fig. 3.** Critical SIFs measured of HMA specimens at −5 ℃, −15 ℃, −25 ℃ under different loading modes of (a) $M^e = 0.0$, (b) $M^e = 0.2$, (c) $M^e = 0.4$, (d) $M^e = 0.6$, (e) $M^e = 0.8$, (f) $M^e = 1.0$.

**(d) Me=0.6**



**(e) Me=0.8**



**(f) Me=1.0**

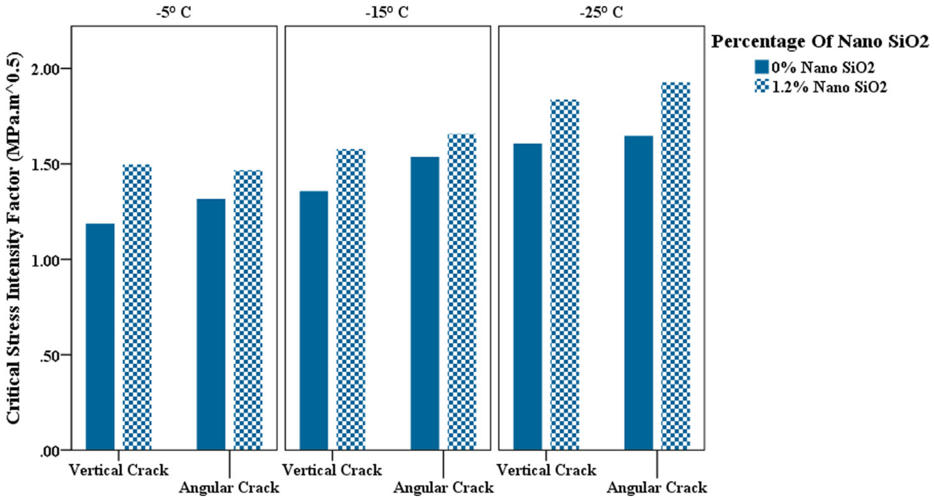


**Fig. 3** (*continued*)

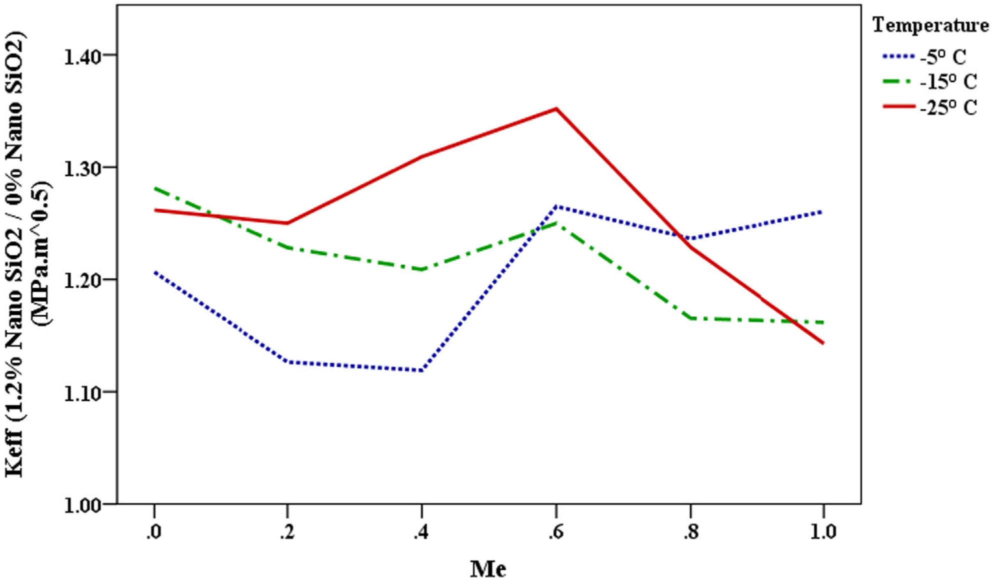


**Fig. 4.** Ratio of $K_{eff}$ for the Nano $SiO_2$-modified HMA mixtures to the base asphalt mixture (vertical crack).

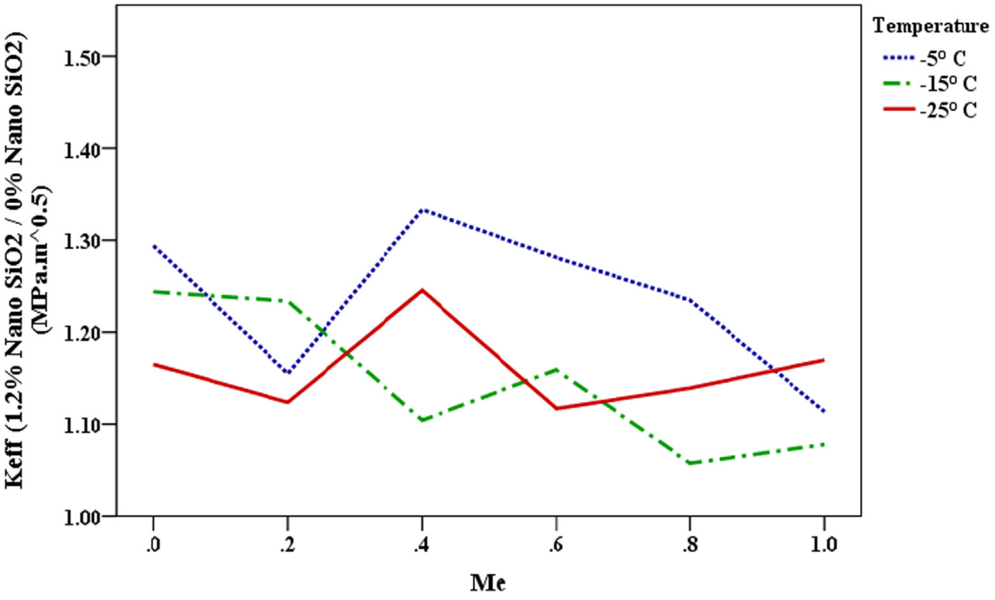


**Fig. 5.** Ratio of $K_{eff}$ for the Nano $SiO_2$-modified HMA mixtures to the base asphalt mixture (angular crack).

1) The addition of 1.2% Nano-Silica improves the fracture resistance of asphalt mixtures because of the increased adhesion between the binder and aggregates. The critical SIFs of modified asphalt mixtures with vertical and angular cracks increased to a maximum value of 35% and 33%, respectively.
2) Decrease of testing temperature from −5℃ to −25℃ causes increases the critical SIFs of asphalt mixtures, and this increase is more highlighted in asphalt mixtures modified with Nano-Silica.
3) By adding Nano-$SiO_2$, the fracture resistance of the HMA mixtures increased for all the loading modes. The highest improvement in critical SIF observed under mixed-mode I/II loading ($M^e$ = 0.4 and $M^e$ = 0.6). Therefore, Nano-$SiO_2$ is more suitable for the mixed-mode I/II loading (i.e., Critical loading)
4) The maximum value of critical SIFs in both modified and unmodified asphalt mixtures was related to pure mode I ($M^e$ = 1).
5) The critical SIF of pure mode II and mode II dominant loadings of the asphalt mixtures with vertical cracks is higher than the asphalt mixtures with angular cracks, while the critical SIF of pure mode I and mode I dominant loadings of the asphalt mixtures with angular cracks is higher than the asphalt mixtures with vertical cracks.

At the end, It should be mentioned the improved intermediate and high temperature performance of Nano-Silica modified asphalt binder and mixtures have been proved before [14,32] and this article indicated the high potential of Nano-$SiO_2$ in enhancing low temperature cracking resistance of asphalt mixture. However, in-

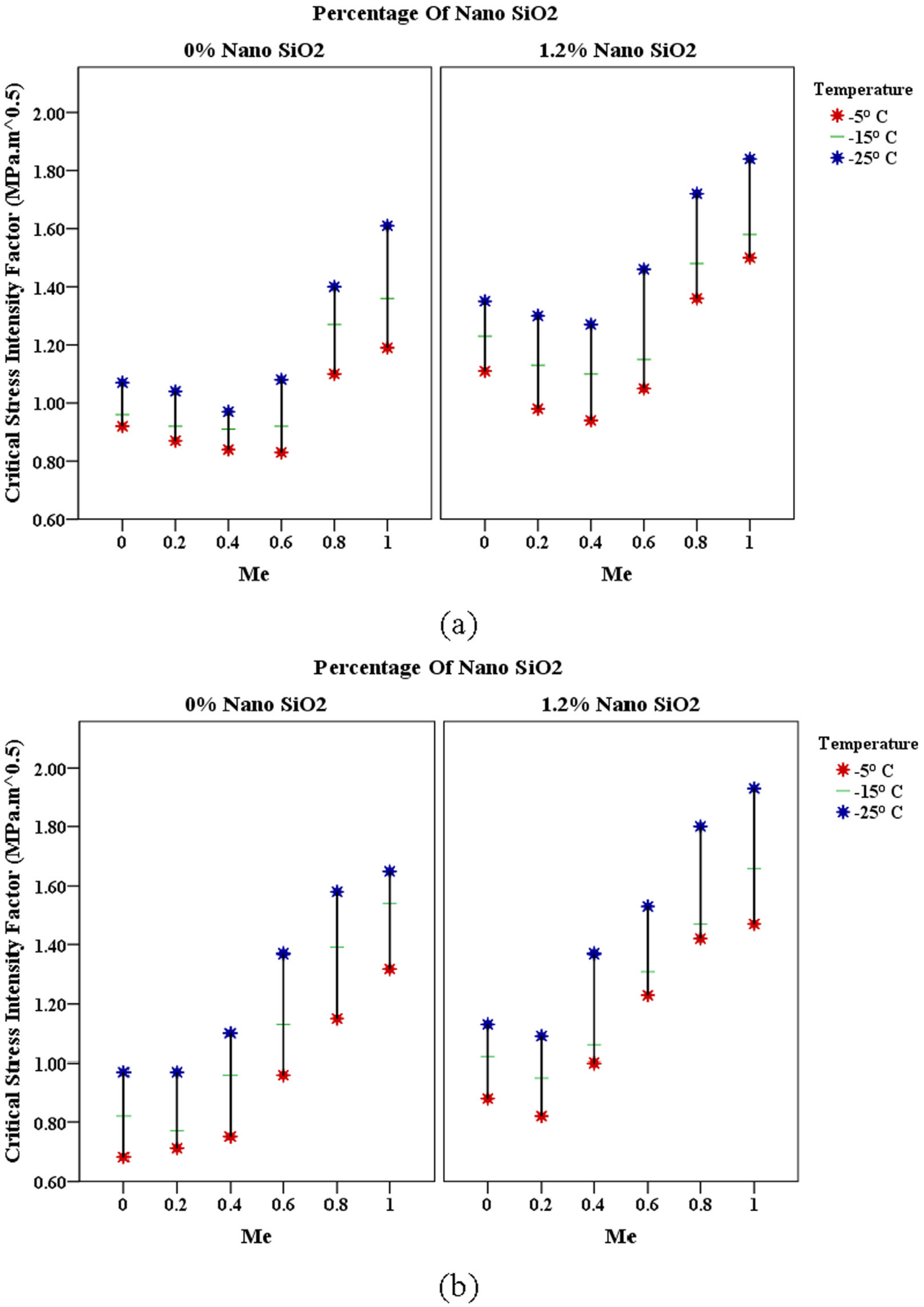


**Fig. 6.** Effect of low temperatures on critical SIFs for (a) vertical crack (b) angular crack.

field evaluation is required to validate the laboratory testing results of Nano-$SiO_2$ modified asphalt mixtures and ensure its positive effect on low-temperature cracking resistance. Moreover, researchers haven't investigated yet the effect of loading rate on the critical SIF of asphalt mixtures. Therefore, it can be a wonderful suggestion for future research.

## 6. Author statement

Dr. Mostafa Sadeghnejad and ms. Roya Ebrahimnia carried out the experiment and wrote the manuscript with support from Prof. Gholamali Shafabakhsh as a supervisor of the project and corresponding author.

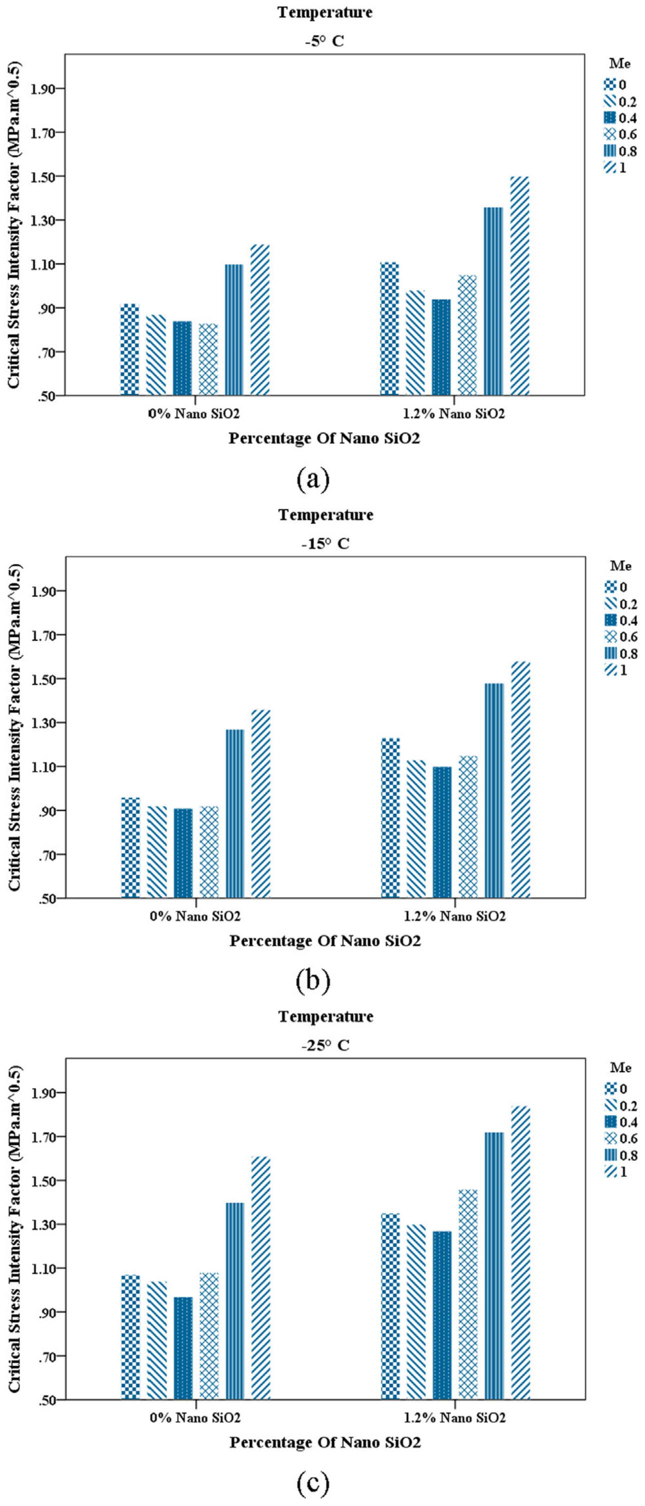


**Fig. 7.** Fracture resistance of the specimens with vertical crack under different loading modes at temperatures of (a)-5℃, (b)-15℃, (c)-25℃.

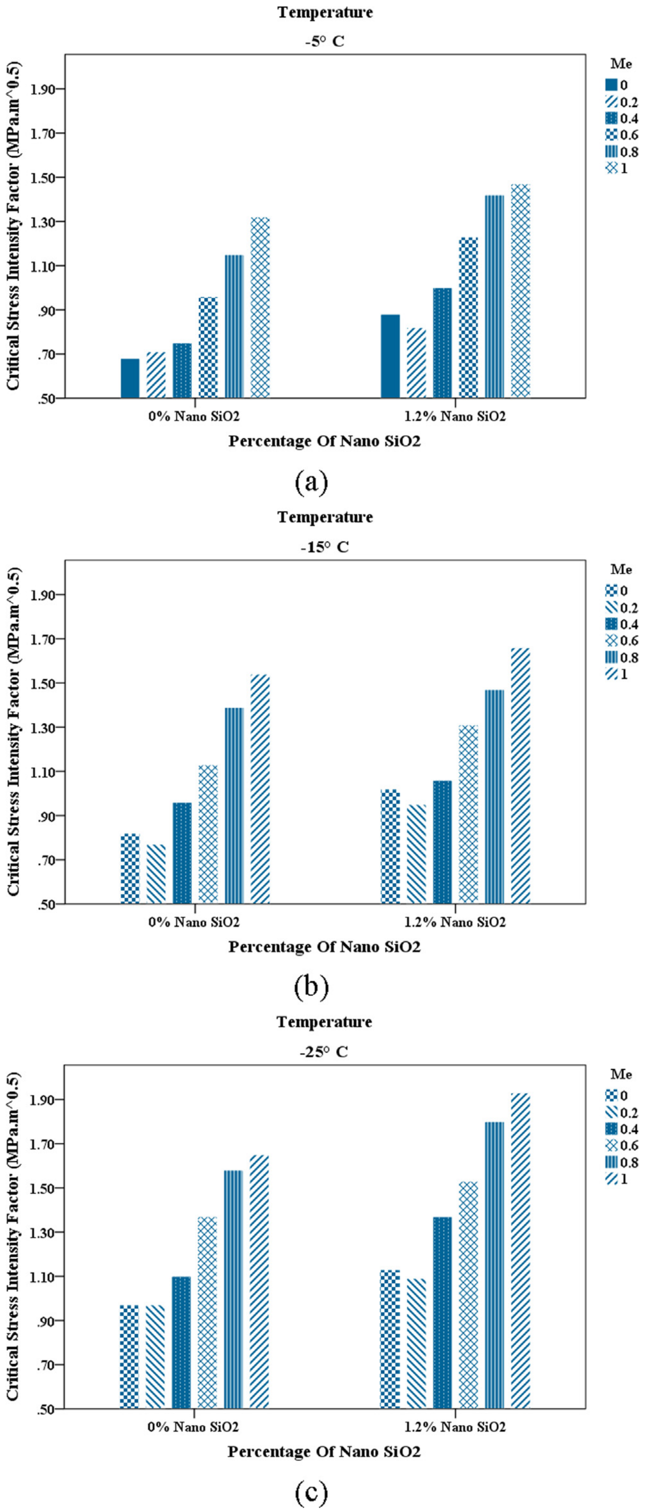


**Fig. 8.** Fracture resistance of the specimens with angular crack under different loading modes at temperatures of (a)-5℃, (b)-15℃, (c)-25℃.

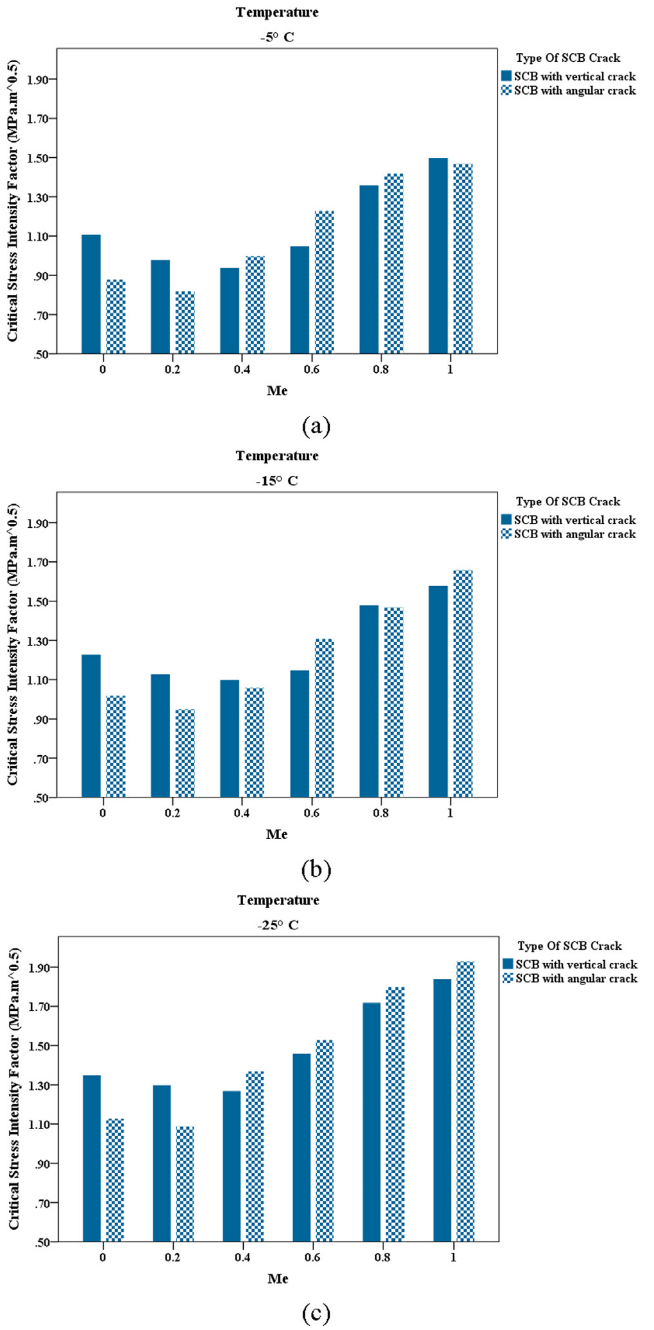


**Fig. 9.** Critical SIFs of modified specimens with vertical and angular cracks at temperatures of (a)-5℃, (b)-15℃, (c)-25℃.

## 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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