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Effect of Temperature on the Stiffness of Polyvinyl Chloride and Chlorinated Polyvinyl Chloride Joints Under Bending

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Abstract: The main objective of this study was to determine the effect of temperature on the bending capacity and stiffness of PVC and CPVC cemented socket joints using test specimens as simply supported beams subjected to different bending points. The tests were conducted under six different temperatures (room temperature, 23°C, a control treatment), 50, 60, 70, 80 and 90°C, three bending points and with a deflection of 55 mm using a hydraulic testing machine. The results show that, at room temperature, the mean maximum bending capacity of CPVC joints was close to that of PVC joints. The rate of decrease in the mean maximum bending force of PVC joints was higher than CPVC joints with an increase in temperature. A dramatic decrease in the mean maximum bending force of PVC joints was observed with an increase in temperature from 60-70°C, where the glass transition temperature of PVC material was within the above stated temperature range. At room temperature, the stiffness of PVC joints was slightly more than CPVC joints. But, as the temperature increased, the rate of decrease in the stiffness of PVC joints was more than CPVC joints. The PVC joints lost 80% and the CPVC joints lost 47.6% of its stiffness with an increase in temperature from 23-90°C. The study showed an excellent potential for the selection of optimum temperature for using PVC and CPVC joints under arid environment.

Key words: PVC joints, CPVC joints, temperature, three point bending, stiffness, bending force, cemented socket joints

INTRODUCTION

Polyvinyl chloride (PVC) pipes can be joined using mechanical joints or solvent cement joints. Solvent cement joints are the most commonly used joints especially for small diameter pipes because they provide a system with the least risk (Lu *et al*., 2000). PVC cemented joints may fail due to cracks through the adhesion between the socket and the pipe interface and through the damage in the sockets or the pipes. When installing piping systems, some changes in the direction may be necessary. So, the response of PVC pipe materials to longitudinal bending is considered to acquire significant advantages especially in buried and suspended applications. Longitudinal bending may be done deliberately during installation to make changes in the alignment to avoid obstructions or it may occur in response to unplanned conditions such as changes in soil properties (Anonymous, 1991). PVC pipes with and without solvent cement joints were tested in four points bending using variable internal pressure (Scavuzzo *et al*., 1999, 1998). They found that the joined pipe specimens with no internal pressure were weaker in fatigue bending than the pressurized pipes. Forte *et al*. (1991) investigated the effect of bending radius and temperature on the service life of Polyethylene (PE) pipe found that as the bending radius increased from 20 D (D = pipe outer diameter) to 40 D, the pipe life increased 13 times while, the service life decreased by 80% due to a temperature rise of 10°C. Similarly, Rahman and Mandal (1995) studied the effect of temperature and the internal pressure sustaining capacity for PVC pipes and noted that there was a remarkable effect of temperature on the mean failure pressure characteristics of PVC pipes. However, with the increase of temperature, the mean failure pressure decreased remarkably. Shi *et al*. (2002) investigated the effect of temperature on the mechanical properties of under fill material and observed that the effect of the temperature on the mechanical properties is much stronger at temperatures around T_g than the temperatures below and above T_g. Chaoying *et al*. (2004) studied the effect of temperature on the dynamic

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mechanical properties of PVC with and without nano-$CaCO_3$. They found that a sudden decrease in the dynamic mechanical properties of PVC occurred at the glass transition temperature. Wan *et al*. (2003) investigated the mechanical properties of PVC-clay Nan composites at different temperatures. They found that the mechanical properties decreased dramatically at glass transition temperature. A dynamic mechanical analysis of glycol modified polyethylene terephthalate (PETG) and poly methyl-methacrylate (PMMA) showed that a sudden change in the mechanical properties of the materials under bending occurred at glass transition temperature of each material (Jae and Cha, 2001). Aarkireyeva and Hashmi (2002) examined the effect of temperature on the fracture parameter of uPVC film. They found that the essential work of fracture is not affected by a temperature rise up to 60°C which is the glass transition temperature of the used material.

The joints are points of weakness in the piping systems, so it is important to study the failure modes of joints when subjected to bending at different temperatures. The main objective of this research was to study the effect of temperature on the maximum bending force and the stiffness of PVC and CPVC cemented sockets to determine the best materials for installing piping system.

MATERIALS AND METHODS

The test specimens were prepared from PVC and CPVC pipes and the sockets manufactured in Saudi Arabia. The pipes were manufactured by extrusion while the sockets were made by injection molding. The PVC and CPVC pipes were manufactured according to the ASTM (American Society for Testing and Material) standards D 1785 and F 441, respectively. The outer diameter of pipes was 26.7 mm and the wall thickness was 4.3 mm. The sockets have outer diameters of 37 mm and a length of 56 mm. The test specimens for the study were designed as simply supported beams subjected to three points bending (Jae and Cha, 2001; Moosa and Mills, 1998). The distance between the beam supports was 420 mm. The bending force was applied at the middle of the beam by a hydraulic testing machine (Al-Naeem and AL-Hashem, 2005). The test specimens were fixed to the moving head of the testing machine while the loading rod and the load cell were attached to the fixed head. The bending force was monitored by using a load indicator connected to the load cell.

Three types of test specimens were tested. The first type of test specimens were pipe segments of 50 cm length. This test was conducted to quantify the effect of the socket joints on the stiffness. The second type of specimens were tested to quantify the contribution of the glue in the joint stiffness. In this test, the specimens were prepared by fitting the pipe segments into the sockets without glue (uncemented joints). The third type of test specimens were used as the main test in which specimens were prepared by using the solvent cement corresponding to each material (PVC and CPVC) as a glue material (cemented joints). In order to make sure that the joint glue reached its steady state, the specimens were prepared and leftover for 15 days before testing. The first and second types of specimens were tested at room temperature only. The third type of specimens were tested at six different temperatures namely 23, 50, 60, 70, 80 and 90°C.

To obtain the testing temperature of 50°C and above, a homogenous temperature through the joint wall was obtained by immersing the test specimens in an automatic digital water bath for 24 h at the desired test temperature. Later on the specimens were taken out from the water bath and insulated to keep their temperature constant. Then, the test specimens were fixed immediately to the testing machine and the insulation material was removed. To keep the specimen temperature constant during testing, it was subjected to a jet of hot air from an electric heater. The distance between the heater and the specimens was adjusted to obtain the desired test temperature around the test specimen. The specimens were loaded up to a deflection of 55 mm (Al-Naeem and Al-Hashem, 2005). The speed of the moving head of the testing machine was adjusted at 2.5 cm min^{-1} (Ollick and Al-Amri, 2000). Each test was replicated three times. The deflection of the test specimens was measured by fixing a ruler having 0.5 mm divisions to the moving head of the testing machine. The motion of the ruler related to a fixed line and the load indicator readings were recorded using a video camera. The video tape was played back using a special video and the play back speed was adjusted to be 1/16 of the recording speed. To increase the deflection measuring accuracy, the picture of the load reading and the ruler divisions was magnified 50 times by connecting the video to a data show. The output picture of the data show was displayed on 2×2 m screen. The readings of the load indicator and the corresponding deflection were tabulated for each 1 mm deflection. The data representing the relationship between the bending force and the deflection were drawn to determine the bending energy. The bending energy is represented by the area under the load deflection curve; therefore, it was obtained by integrating the fitting equations. A QBASIC program was written to perform these integrations using 0 and 55 mm as the lower and upper integration limits, respectively.

The local stiffness (K_L) of the test specimen at a certain point is defined as the rate of change of the bending force (F) with respect to the deflection (Δ) at this point ($K_L = \delta F/\delta\Delta$). In this study, the local stiffness was taken as the slope of the fitting line which fits the relationship between the load and the corresponding deflection over a deflection intervals of 2 mm (i.e., 0-2, 2-4, 4-6,……………,38-40).

RESULTS AND DISCUSSION

Effect of temperature on the maximum bending force: Figure 1 and 2 shows the relationship between the bending force and the corresponding deflection of pipes, cemented joints and uncemented joints at room temperature for PVC and CPVC materials, respectively. The integration results are shown in Table 1.

The bending energy of cemented PVC and CPVC joints (PVC and CPVC) was 31 and 53.3%, respectively more than the uncemented joints. i.e., the effect of CPVC cement on the joint toughness was 1.72 times more than that of PVC cement (Table 1). Also, the bending energy of PVC pipes was 9.9% more than the CPVC pipes. In the case of un-cemented joints, the bending energy for PVC joint was 13.6% more than that of CPVC joints. Similarly, for cemented joints, the bending energy for CPVC was 2.9% more than that of PVC (The effect of CPVC cement inverted the ranking of the other two conditions). These phenomena occurred because the PVC pipe segments were observed to pull out the socket during loading. On the other hand the pull out phenomena did not exist in CPVC joints. However, a bending in the pipe segments was observed at the socket edge_

The relationship between the mean bending force and the corresponding mean deflection for PVC and CPVC joints at different temperatures (23, 50, 60, 70, 80 and 90°C) is shown in Fig. 3, 4, respectively. It was also observed that the bending force and consequently the bending moment capacity of PVC joints decreased with respect to the temperature at higher rates than the CPVC joints. A sudden drop in the bending force capacity of PVC joints was noted with the change in temperature from 60 to 70°C (Fig. 3). This sudden drop exists because the glass transition temperature of PVC material was within this temperature range [Tg = 60°C (Shi *et al.* 2002), T_g = 62.5°C (Chaoying *et al.*, 2004), Tg = 72°C (Aarkireyeva and Hashmi, 2002)]. Since CPVC pipes are used for higher

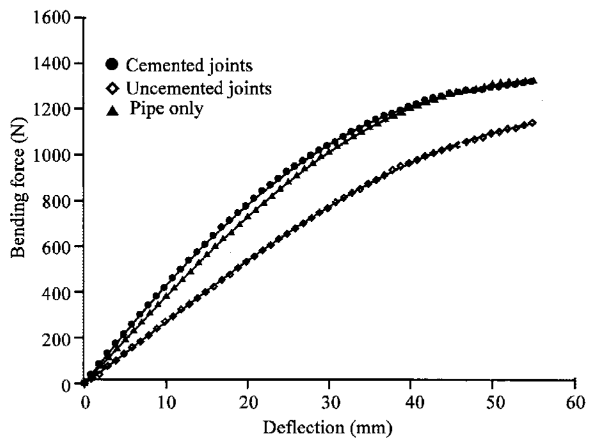

Fig. 1: Relationship between the bending force and the corresponding deflection of PVC cemented joint, uncemented joint and pipes

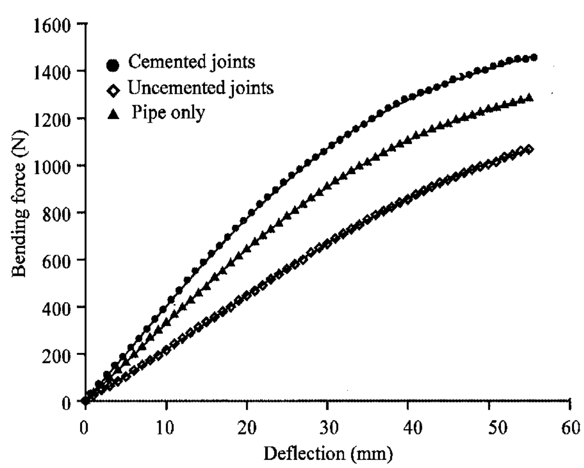

Fig. 2: Relationship between the bending force and the corresponding deflection of CPVC cemented joint, uncemented joint and pipes

Table 1: Bending energy (joules) for pipes and joints (uncemmnted and cemented) of PVC and CPVC at room temperature (23°C)

Material	PVC	CPVC
Pipes only	46.7	42.5
Uncemented joints	36.7	32.3
Cemented joints	48.1	49.5

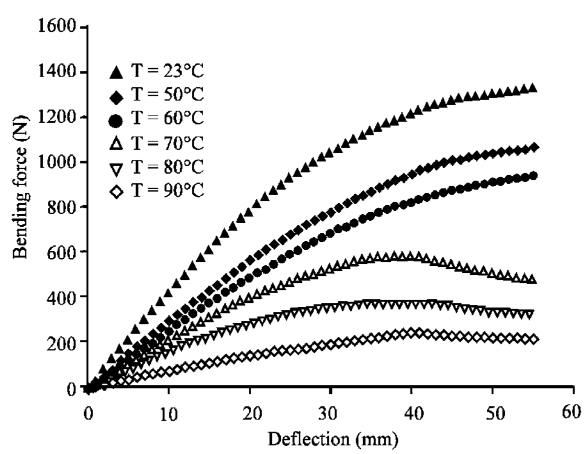

Fig. 3: Relationship between the bending force and the corresponding. deflection of PVC joints at different temperatures

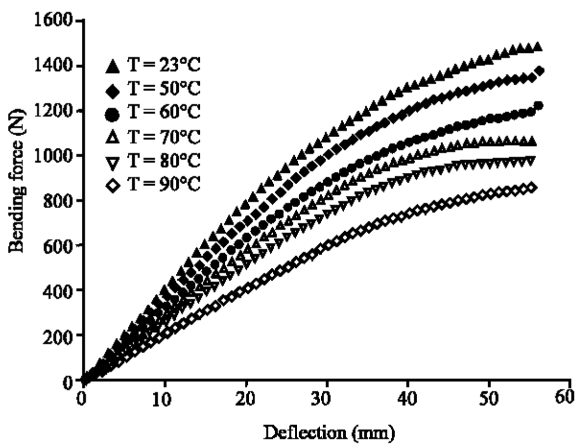

Fig. 4: Relationship between the bending force and the corresponding deflection of CPVC joints at different temperatures

temperature applications, it is expected that the effect of temperature on the loading capacity must be lower than the PVC pipe material. However, there was no sudden drop in the bending force capacity of CPVC joints due to increase in temperature (Fig. 4).

Figure 5f describe comparison between the PVC and CPVC joints in terms of force-deflection relationship. At room temperature (23°C), the relationship for the two materials coincided up to a deflection of 25 mm. In the case of deflection values more than 25 mm, the force-deflection relation of PVC joints starts to deviate to lower values than those for the CPVC joints. This behavior could be attributed to two reasons (1) due to the fact that the plastic deformation of PVC is higher than the CPVC, i.e., the effective deflection of CPVC is higher than the PVC material (effective deflection = total deflection-plastic deformation). (2) it is related to the adhesion materials because the damage in the adhesion between the pipe and the socket for PVC joints was observed at lower deflection values than the CPVC joints. For the testing temperatures of 50 and 60°C (Fig. 5 b,c) and at the same deflection value, the bending force of PVC joints was lower than the CPVC joints over the entire deflection range. It was also noticed that the difference in the mean bending force between PVC and CPVC joints is approximately the same for the two testing temperatures. With respect to testing temperatures of 70, 80 and 90°C (Fig. 5d-f, respectively), the difference between the mean bending force of the two types of joints increased particularly at 90°C. Results further reveal that in the case of PVC joints at the deflection values between 35 and 40 mm, the mean bending force decreased with increase in the deflection values. These phenomena occurred because the pipes were observed to be pulled out from the socket after these deflection values.

A relationship was developed between the mean maximum bending force and the test temperatures for PVC and CPVC joints (Fig. 6). The data of uncemented joints at room temperature was also included. The sudden decrease in the maximum bending force of PVC joints between 60 and 70°C temperatures occurred because the glass transition temperature of the PVC material is within this temperature range (Shi *et al.* 2002; Chaoying *et al.*, 2004; Aarkireyeva and Hashmi, 2002). At room temperature, the mean maximum bending force of the cemented joint of PVC and CPVC materials increased by 16 and 36%, respectively than the un-cemented joints. It was further noticed that over the entire temperature range, the mean maximum bending force of PVC and CPVC materials decreased by 84 and 42%, respectively. However, in the case of PVC, 35% of this percentage occurred due to the increase in temperature from 60 to 70°C.

Effect of temperature on the stiffness of joints: The results reveal that for the PVC pipe joints at higher temperatures and at a deflection value about 40 mm, the load decreased with the increase in deflection value (i.e., a negative stiffness). Therefore, the analysis of the two materials was limited to the deflection values ranging between 0 and 40 mm.

Figure 7 and 8 show A relationship was developed between the deflection and the local stiffness of PVC and CPVC pipe joints (Fig. 7, 8). It was found from the data in two figures that the local stiffness was approximately constant for the two materials (PVC and CPVC pipes) over the first stage of deflection at different test temperatures, At the next stage of deflection, the local stiffness started to decrease with an increase in the deflection value. The regions of constant local stiffness seemed to extend over the deflection values equal to that which correspond to the elastic limit (Ollick and Al-Amri, 2000), while the regions of steeper slope correspond to the elastic-plastic regions. The yield stress decreased with an increase in temperature, so the elastic region interval decreased thus resulting in the downturn movement of point to the left as shown in Fig. 7 and 8.

Figure 9 describe the relationship between the average values of local stiffness in the elastic region and the test temperature both for the PVC and CPVC joints. The data of uncemented joints and pipes at room temperature was also considered. The slope of the fitting lines represents the rate of decrease of stiffness with respect to temperature. Table 2 shows the average decreasing rates of stiffness both for the PVC and CPVC cemented joints

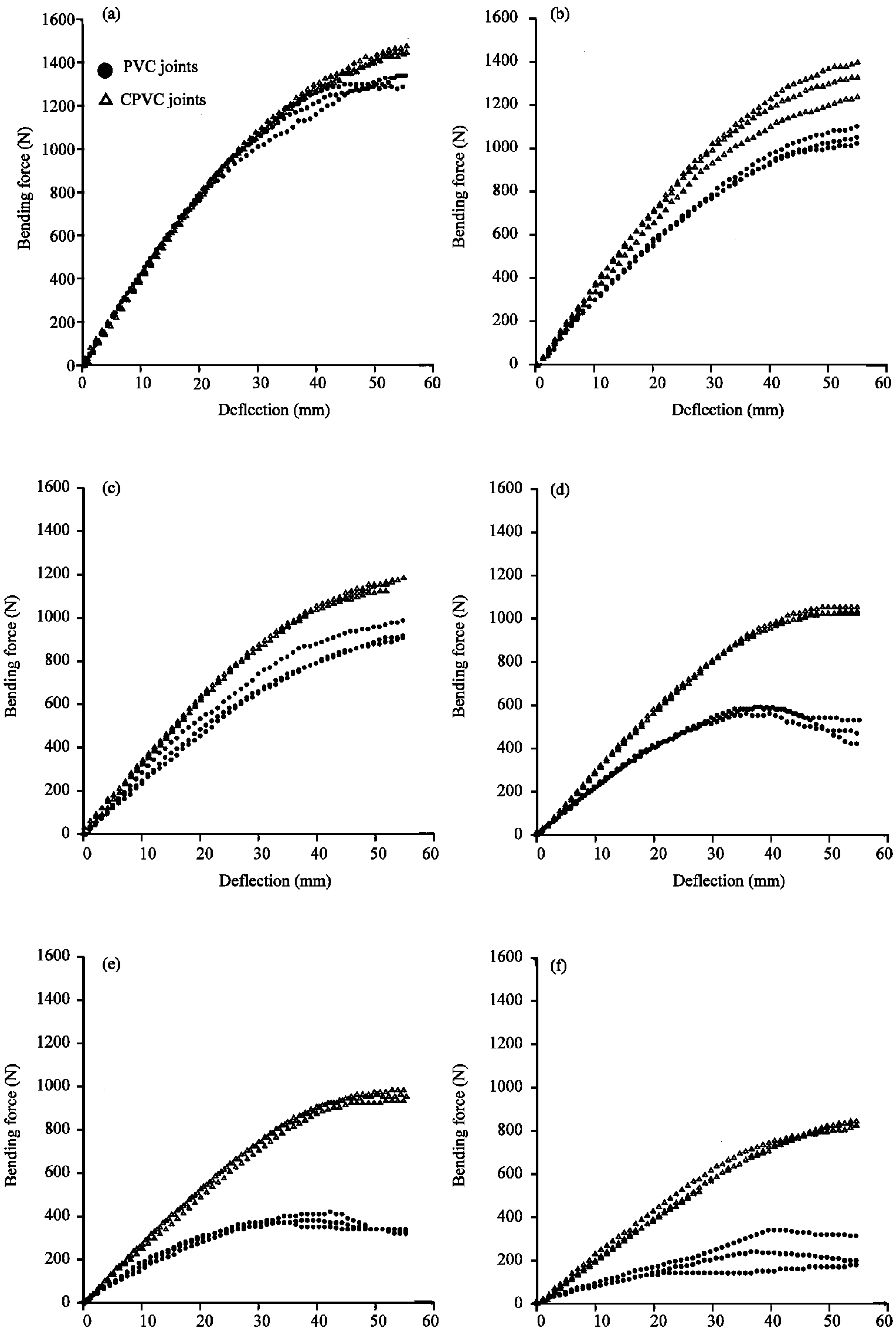

Fig. 5a-f: Comparison between the bending force and the corresponding deflection of PVC and CPVC joints at different temperatures (a) 23, (b) 50, (c) 60, (d) 70 (e) 80 and (f) 90°C

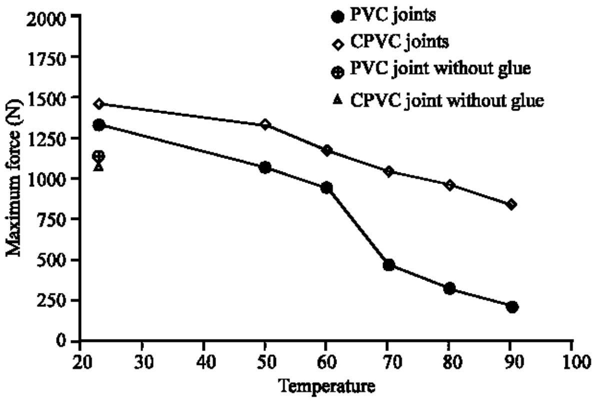

Fig. 6: Relationship between the maximum bending force and test temperatures of PVC and CPVC joints

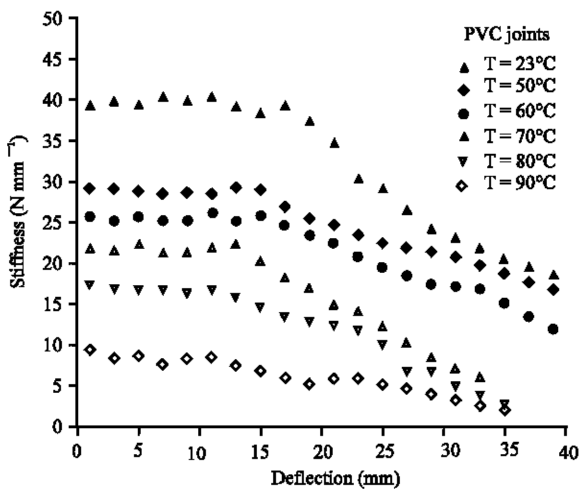

Fig. 7: Relationship between the local stiffness and deflection of PVC joints

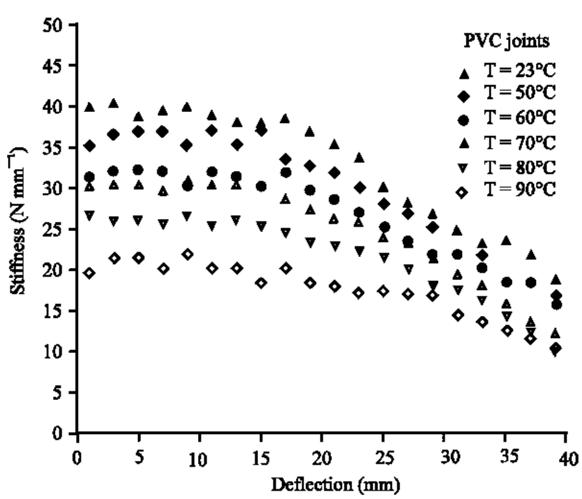

Fig. 8: Relation between the local stiffness and deflection of CPVC joints

Table 2: Average decreasing rate of stiffness of PVC and CPVC joints per a°C (N mm^{-1} per °C)

Pipe material	Temperature range (°C) 23-50	50-60	60-70	70-80	80-90
PVC	0.34	0.41	0.57	0.45	0.85
CPVC	0.17	0.25	0.27	0.34	0.57
PVC/CPVC	2.00	1.64	2.10	1.30	1.50

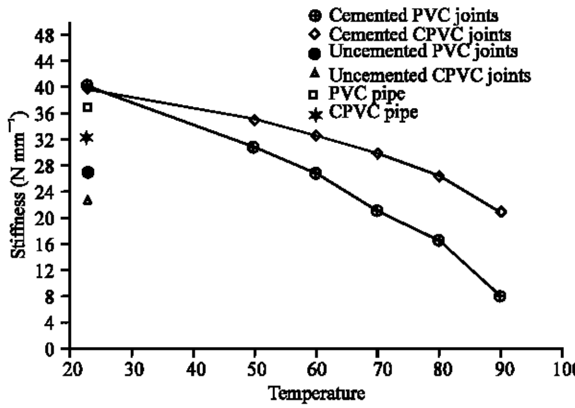

Fig. 9: Relationship between the average stiffness and test temperature in the elastic loading region for cemented and un-cemented joints and pipes

at different temperatures. However, at any given temperature range, the decreasing rates of mean stiffness of PVC is higher than the CPVC. The decreasing rate of PVC joints changes in non-uniform manner, whereas, the decreasing rate of CPVC increases gradually with the increase in temperature. At the temperature range of 23-50°C, the decreasing rate of mean stiffness of PVC joints was 2 times higher that the CPVC joints. Which means that CPVC joints were not sensitive to the corresponding change in temperature at the lower temperature levels. However, at a temperature range between 60-70°C, the ratio between the decreasing rates of mean stiffness of PVC and CPVC joints increased again to 2.1 which could be related to the effect of the glass transition temperature of PVC material.

At room temperature, the local stiffness of the cemented PVC or CPVC joints was 50 and 74% higher, respectively than the un-cemented PVC or CPVC joints (Fig. 9).

On relative basis, the percentage decrease in the stiffness at different temperatures relative to the stiffness at room temperature (23°C) is presented in Table 3 and Fig. 9. The values of PVC joints show that the joint stiffness decreased approximately 1% per °C with the change in temperature from 23 to 80°C. whereas, the stiffness decreased up to 2.1% per °C with the change in temperature from 80 to 90°C. However for the CPVC joints,

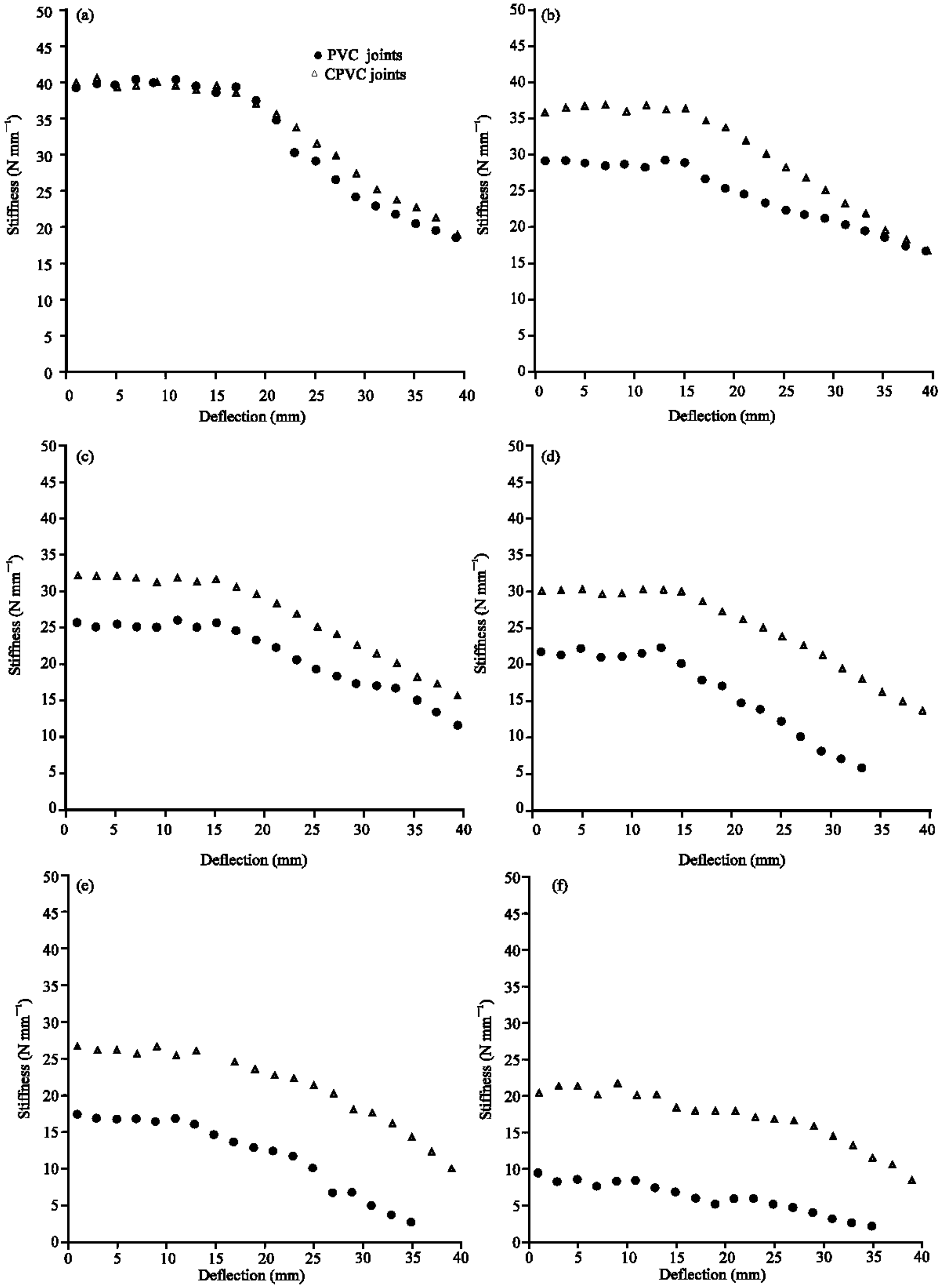

Fig. 10: Comparison between the local stiffness and the corresponding deflection of PVC and CPVC joints at different temperatures (a) 23, (b) 50, (c) 60, (d) 70, (e) 80 and (f) 90°C

Table 3: Mean percent decrease in the stiffness of PVC and CPVC joints relative to the stiffness at room temperature

Material	Temperature (°C) 50	60	70	80	90
PVC (%)	29.00	37.20	47.60	58.90	80.00
CPVC (%)	9.60	19.00	25.80	33.20	47.60
PVC/CPVC	3.02	1.96	1.85	1.77	1.68

the joint stiffness decreased approximately 0.5% per °C with the change in temperature from 23-80°C, whereas, the stiffness decreased by 1.44% per °C with the change in temperature from 80 to 90°C.

Figure 9 shows a comparison between the stiffness of pipes, cemented and uncemented joints of PVC and CPVC materials at room temperature. For pipes and uncemented joints, the difference between the average stiffness of PVC in elastic region and that of CPVC was 4.5 N mm^{-1}. Whereas, for the cemented joints of PVC and CPVC joints, this difference was only 0.6 N mm^{-1}. The constant difference in case of pipes and uncemented joints existed because the stiffness depends on the properties of the materials. While in the case of cemented joints, the stiffness depends jointly on the properties of both the materials and the solvent cement properties. This suggests that the contribution of CPVC cement in the stiffness of joints was higher than the contribution of PVC cement.

Figure (10a-f) describe a comparison between the local stiffness of PVC and CPVC cemented joints and the corresponding deflection at different temperatures. As mentioned earlier, the stiffness-deflection relationship has two stages. The first stage has constant stiffness and corresponded to the elastic-deflection region, while the second stage has steeper slope and corresponded to the elastic-plastic deflection region (Ollick and Al-Amri, 2000). At room temperature the two joint materials approximately coincide over the elastic region while in elastic-plastic region, the stiffness of PVC joints deviates and has low values. As the temperature increases, three phenomena take place. The first one is the movement of the stiffness-deflection relation of the two materials to lower values. The second is the difference between the stiffness of the two materials which increased with increasing temperature. The third is the point of down turn which moves to the left with an increase in temperature thus indicating a shorter elastic region. Since the elastic region depends on the yield stress of the material and consequently the yield stress decreases with increasing temperature and this will ultimately reduce the elastic region.

CONCLUSIONS

The decreasing rate of the mean maximum bending force and the mean stiffness of PVC joints was higher than the CPVC joints at different temperatures. With the increase in temperature from the room temperature to 90°C, the mean maximum bending forces of PVC and CPVC joints reduced to 16 and 58%, respectively. The mean stiffness of PVC and CPVC joints reduced to 20 and 52.4%, respectively as compared to the mean stiffness at room temperature. However, at any given temperature, the contribution of CPVC cement in the stiffness of joints was higher than that obtained for the PVC cement. Based on the study results, CPVC cemented joints are recommended for used in most cases rather than the PVC cement joints, especially for the buried and suspended applications to provide long durability.

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