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Investigation of Deflection and Cracks in Reinforced Concrete Solid Slabs as a Function of Thickness Using Staad Pro and Tekla Tedds

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Abstract

In this study, the effect of variation of thickness of slab on the deflection and crack width of solid slabs were analysed. The thickness of the slab were varied by 150 mm, 175 mm and 200 mm. The design conditions also varied were concrete grade, spacing of reinforcement and size of reinforcement. A two-way slab of size 6 m by 5 m was loaded with varying dead loads and constant live loads and analysed in StaadPro to obtain the internal stresses. Thereafter, the results of the internal stresses were applied in Tekla Tedds software while varying the design conditions to examine the effect on deflection and crack widths. The results obtained showed that as the thickness of the slab increases, the allowable span/effective depth ratio (l/d) increases which implies that the slab is less likely to fail deflection check at higher thickness. For cracking, as the concrete thickness increases, the crack width becomes smaller. Average increase in allowable l/d for different slabs was 13% while an average of 41% change in the values was observed for the crack width as the thickness of the slab was varied. Increase in concrete grade was observed to cause an average of 17% increase in the allowable l/d values. However, in the evaluation of the crack width, the maximum change brought upon by change in the grade of concrete was just 0.8%. Increasing bar size and reducing bar spacing also helped to reduce slab susceptibility to deflection and cracks.

1. Introduction

Slab is one of the most important structural elements in buildings and most civil engineering structures. In reinforced concrete slabs, reinforcement (threaded rods) are embedded in concrete to form a solid mass that has large length/width to thickness ratio and thus it is often identified as plate. Slabs according to functions can be solid slabs, ribbed slabs, waffle slabs and flat slabs while according to structural arrangement, we have one-way slab, two-way slab, cantilever slab etc [1].

When a slab is loaded, it experiences internal stresses which lead it to deflect under the load. When these deflections become excessive, they can lead to crack on the underside and surface of the slabs [2] which can be classified as failure. This action counteracts the purpose of design which requires that the building should be safe against collapse at the ultimate limit state and stiff enough against excessive deflections at service loads [3]. Producing satisfactory designs requires that the magnitude of service loads lies within permissible limits [4]. This is the principle upon which the limit state design applicable in Eurocode 2 (EC 2) is based [5].

To avoid excessive deflections in buildings, it is necessary to control the deflection at the design stage, at the construction stage as well as at the use stage of the slab. At the design stage, the principles of deflection control applicable to BS 8110 and EC 2 are similar and chiefly consist on verification of the allowable span/effective depth ratio of the slabs which is identified as being limited because all factors affecting deflection are included in one parameter, depth [6]. To ensure satisfactory deflection using this method, the slab depth can be increased, the dead loads can be adjusted, the area of reinforcement can be increased and the span of the slab can also be reduced [7]. At the construction stage, excessive construction load associated with fresh concrete, formwork, and materials on slabs has contributed to the failure of slabs [3]. A number of researchers have investigated the problems of deflections and cracks in slab and some of their research outputs are outlined in the following paragraph.

[8] Carried out experiments to analyse how crack widths are influenced by thickness in rigid pavements slabs. They tested three slabs of 100 mm, 150 mm and 200 mm thickness respectively. Recordings and observations were made at 2 kN load applications until 180 kN. Their research findings showed that the slab with the least thickness exceeded the allowable crack width as opposed to the other two that remained below 0.3 mm even at the maximum load. Using this, they were able to decide that crack widths decrease with increase in slab thickness.

[9] Made an observation on the effect of concrete grade on slab deflection. Different concrete grades were considered while doing calculations to test the effectiveness of the deflection check using method proposed by EC 2. According to their findings, high concrete strength, leads to small cracks and a reduction in the slab's deflection.

While evaluating crack width in flexural reinforced concrete beams, [10] observed that increasing the depth of the beam and the reinforcement diameter led to a decrease in crack width. This observation was made after calculating crack width using the formulas provided by different codes.

[11] Researched the factors affecting crack width and spacing in reinforced concrete beams. The results of their research revealed that bar diameter, effective width of the bar per bar, concrete cover and effective spacing were the most significant parameters affecting crack width in beams.

[12] Indicated that increasing the section depth of a member reduces concrete tensile strength which in turn increases stiffness. In other words, deflection is reduced drastically.

Studies on deflection carried out by [13] and [14] showed that slabs with lesser thicknesses are susceptible to cracking and deflection than those with considerably more depth.

As pointed by [6], the use of single parameter of depth to control deflection in buildings is insufficient because of the numerous factors that affect deflection in different conditions. Besides, the occurrence of excessive deflection and cracks in slabs often requires enormous time and resources expense to remedy such. With the advent of powerful modeling and simulation software such as STAADPro and Tekla Tedds, it is possible to model slab in different conditions, assign different thicknesses and loads and observe the deflection and crack susceptibility of the slab under the different assigned loads. This can help to draw conclusion on the most suitable thickness of slab to withstand deflection and prevent cracks under load.

1.1 STAADPro and Tekla Tedds

STAAD Pro stands for Structural Analysis and Design Program. It is a structural analysis and design program developed by Research Engineers International at Yorba Linda, California in 1997. Today it is owned by Bentley System Inc. The software allows engineers to analyse and design structures of all sizes and forms with materials such as concrete, timber, steel and aluminum.

Tekla Tedds is easy-to-use software from Trimble Incorporated that is used to generate accurate results for engineering calculations. With Tekla Tedds, time spent on manual calculations can be cut down drastically with the assurance of error free results.

2.0 Methodology

The variable parameter for this study consists of the slab thickness, size and spacing of reinforcement, as well as the concrete grade which are properties that affect the strength and stability of a slab element. The dependent parameters were deflection and cracks. In essence, when the variable parameters are adjusted, the powerful tools in these software would be used to check the effect of their variation on deflection and cracks on the slab. The first floor slab plan of an office building (Figure 1) was taken as a case study and a panel was chosen as the test panel. Panel 1 was taken as the test panel. In the panel, the dimensions are 5 x 6 where 5 stands for 5 m, and 6 stand for 6 m. All other dimensions are also in metres.

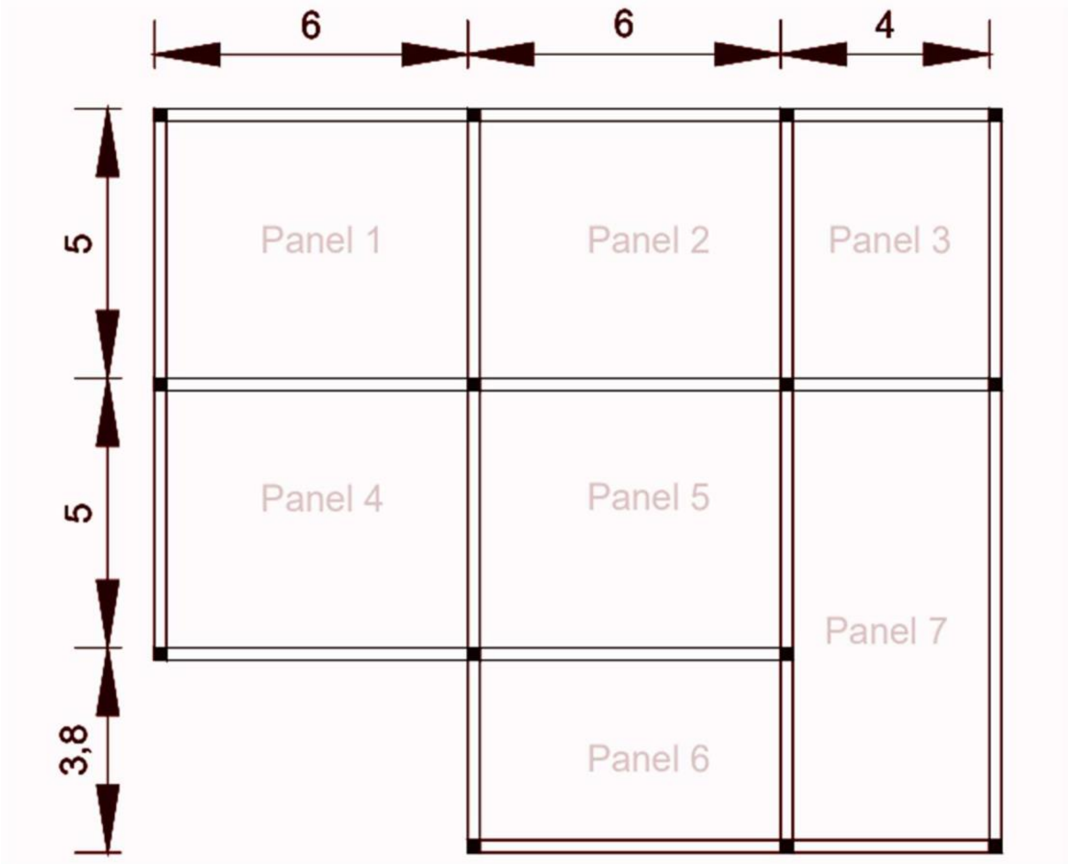

Figure 1: Floor plan of an office building

The test panel was first modelled in StaadPro to determine the internal stresses (Figure 2 – 5), afterwards, the internal stresses were taken to the Tekla Tedds to check the deflection and cracks. The parameters considered in the model include:

Slab type design: Two-way slab
Support condition: Two adjacent edges are discontinuous (condition for panel 1 which was used as the test panel)
Slab dimensions: long span direction, l_y = 6 m; short span direction, l_x = 5 m
Slab thicknesses: 150 mm, 175 mm and 200 mm
Characteristic strength of reinforcement, f_{yk}: 500 N/mm^2
Characteristics strength of concrete (Concrete grade): (15, 20, 25, 30, 35, 40, 45) N/mm^2
Concrete cover, Cc: 30 mm
Characteristic permanent action, G_k: varies with slab thickness
Characteristic variable action, Q_k = 3.0 kN/m^2
Spacing of reinforcement bars: 150 mm, 200 mm, 250 mm, 300 mm
Sizes of reinforcement: 10 mm, 12 mm, 16 mm

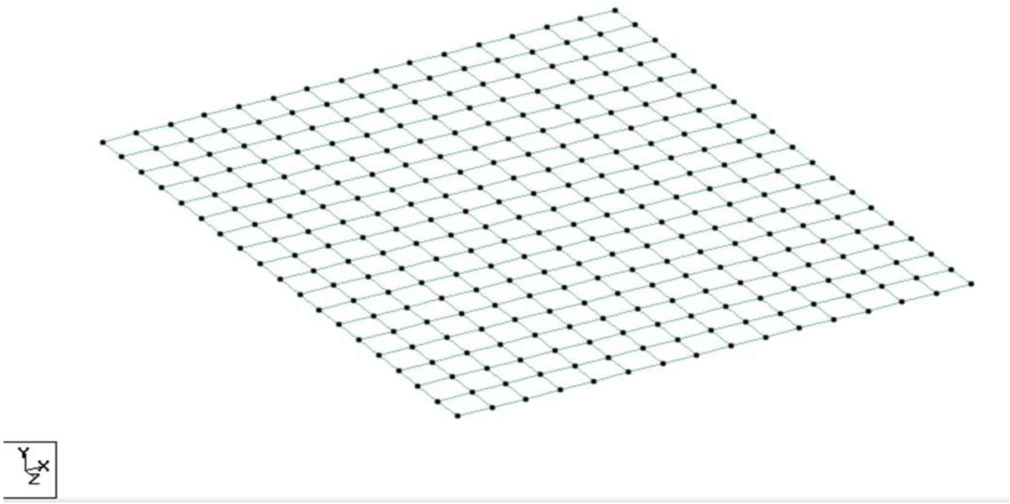

Figure 2: Meshing the slab/plate element.

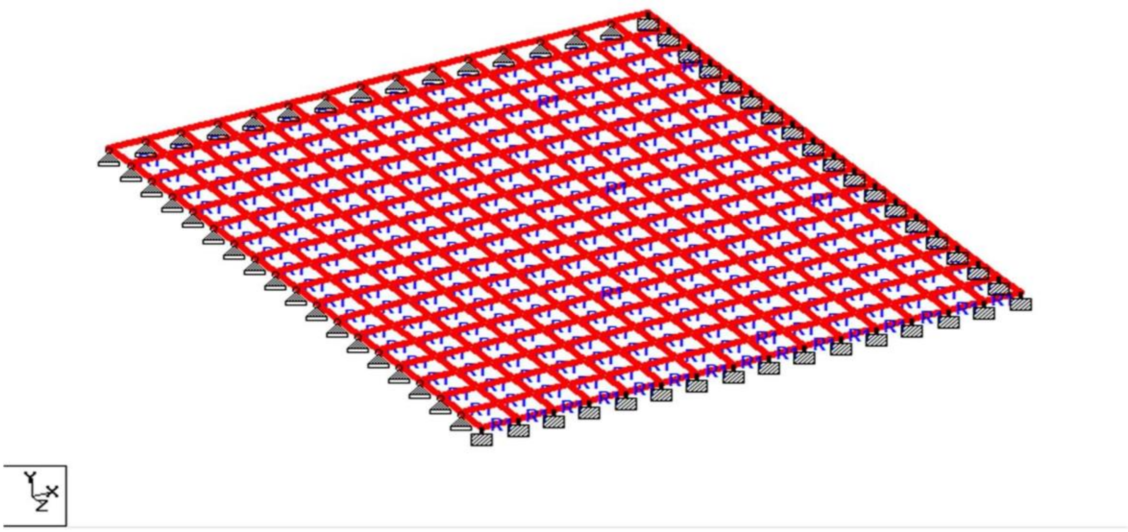

Figure 3: Adding the properties of the slab (thickness and support conditions)

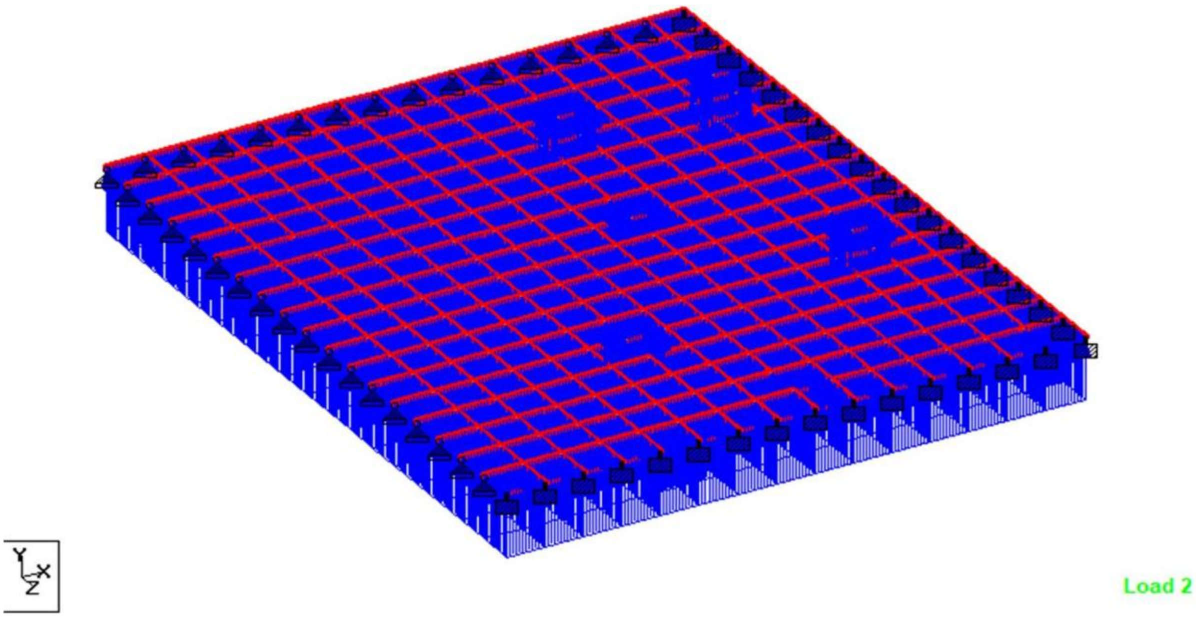

Figure 4: The slab element after loading

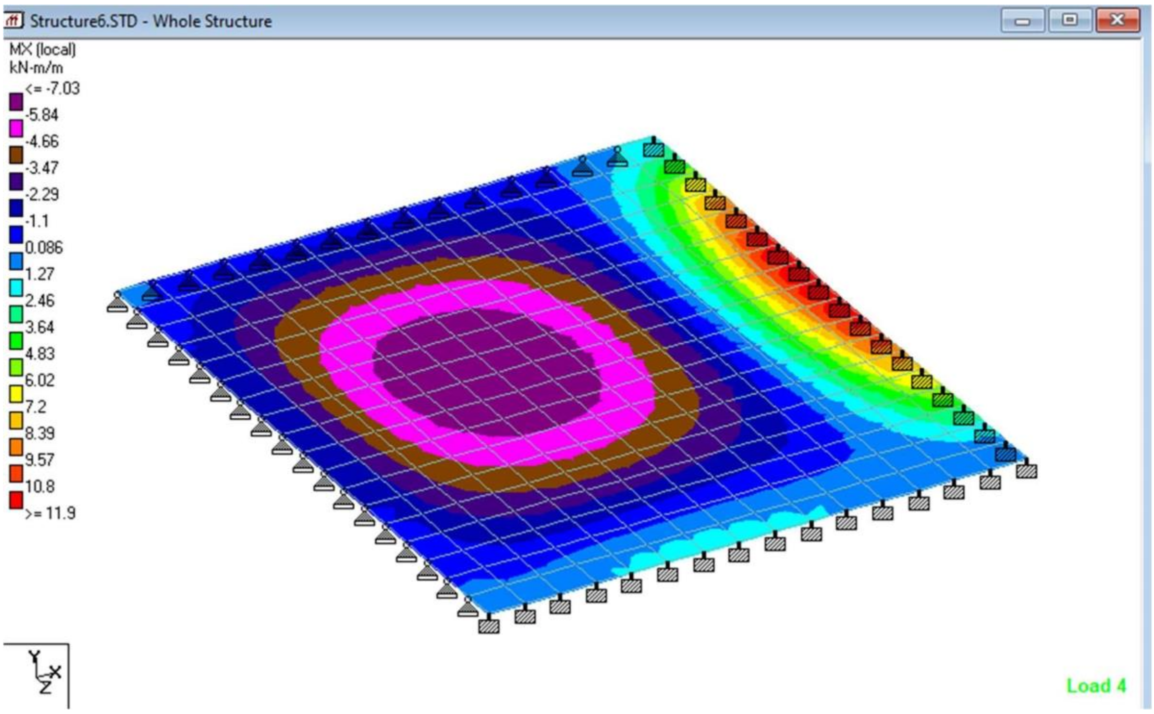

Figure 5: Plate stress diagram which depicts the bending moments on the slab.

2.1. Limitations of Research Methodology

Creep and shrinkage are two unavoidable factors that affect deflection and cracking in concrete. However, it is usually ignored by civil engineers when making serviceability state calculations except in special cases such as long span slabs and cantilevers.

Creep reduces the modulus of elasticity of the concrete, causing a reduction of strength and an increase in deflection. Shrinkage reduces volume thereby causing tensile strain in the concrete, ultimately leading to cracks. Excessive crack-width and deflection affect the durability and strength of the concrete.

Though there are equations and software such as Atena 2D that incorporate the effects of creep and shrinkage for serviceability calculations, these equations were not considered instead the 'deemed-to-satisfy' approach used was believed to take care of the effects of creep and shrinkage in concrete.

3.0 Results and Discussion

The slabs were categorized as Slab A, B and C based on the varying slab thicknesses and characteristics dead load on the slab. Slab A was 150 mm thick with a characteristics dead load of 7.5 kN/m^2. Slab B was 175 mm thick with characteristics dead load of 8 kN/m^2. Slab C was 200 mm thick with characteristics dead load of 8.5 kN/m^2. The characteristics live load with the value of 3 kN/m^2 was constant across all the slabs.

3.1 Effects of Parametric Variations on the Deflection of Slab

The effects of the variations of concrete grade, spacing of reinforcement, size of reinforcement and thickness of slab on the deflection of the slab were examined and following results were obtained.

3.1.1 Effect of Concrete Grade and Spacing on the Deflection of Slab

Figure 6 - 14 shows the variation of concrete grade and spacing with the deflection of the slab based on the allowable span/effective depth ratio (allowable l/d).

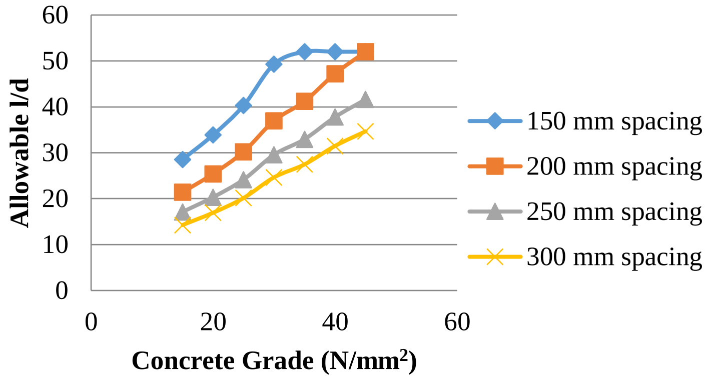

Figure 6: Variation of concrete grade with allowable l/d for 10 mm reinforcement for Slab A

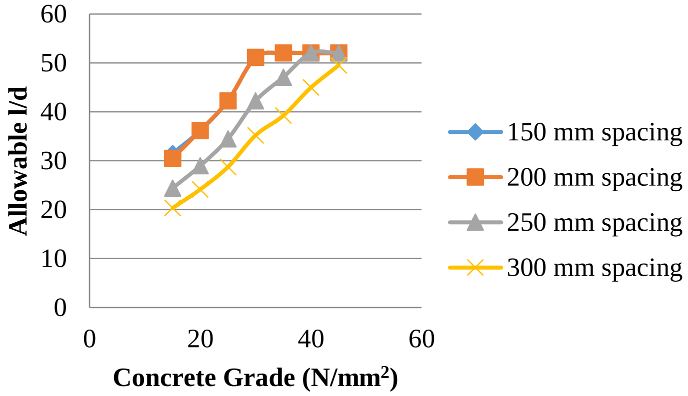

Figure 7: Variation of concrete grade with allowable l/d for 12 mm reinforcement for Slab A

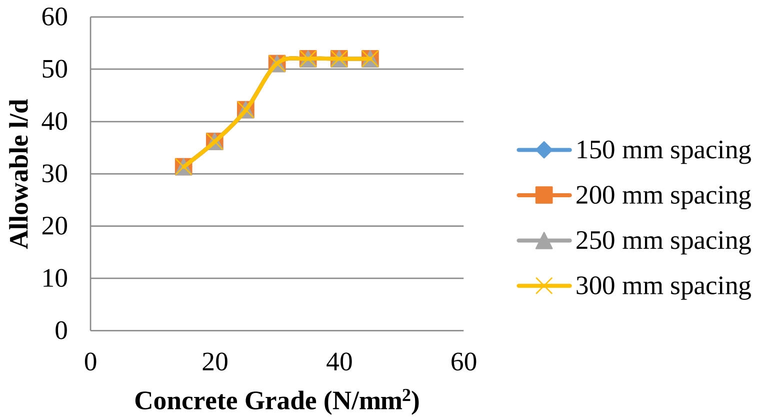

Figure 8: Variation of concrete grade with allowable l/d for 16 mm reinforcement for Slab A

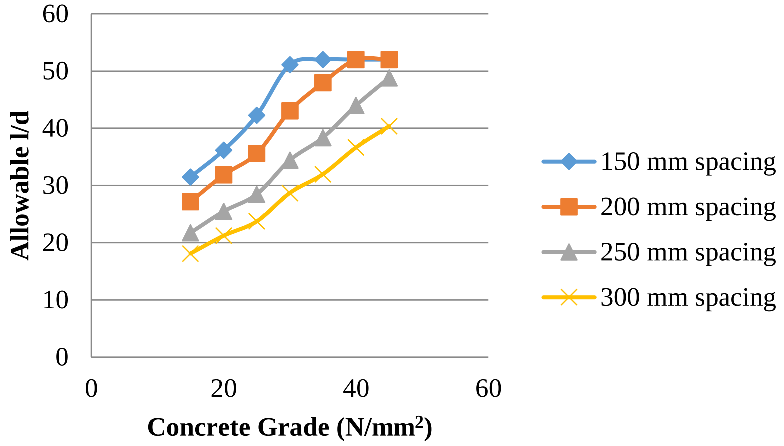

Figure 9: Variation of concrete grade with allowable l/d for 10 mm reinforcement for Slab B

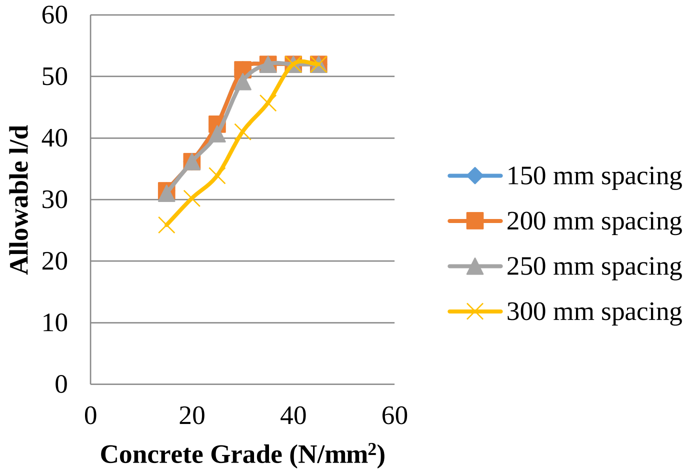

Figure 10: Variation of concrete grade with allowable l/d for 12 mm reinforcement for Slab B

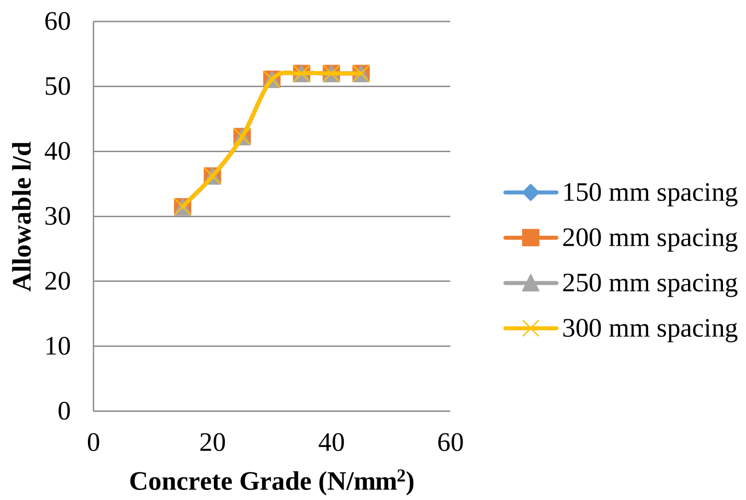

Figure 11: Variation of concrete grade with allowable l/d for 16 mm reinforcement for Slab B

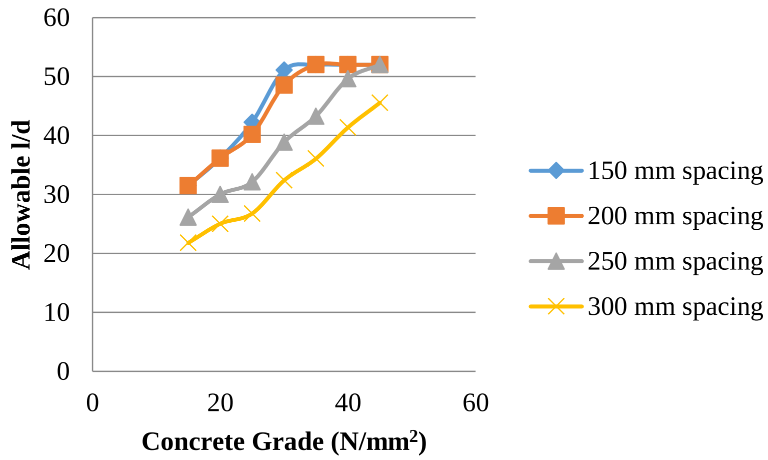

Figure 12: Variation of concrete grade with allowable l/d for 16 mm reinforcement for Slab C

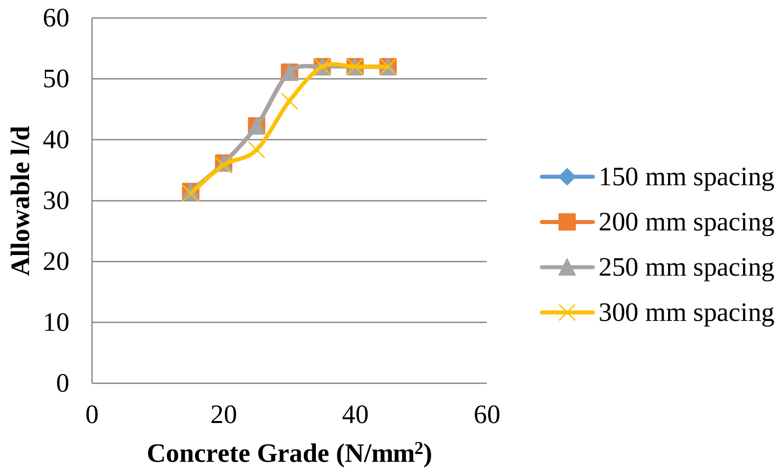

Figure 13: Variation of concrete grade with allowable l/d for 16 mm reinforcement for Slab C

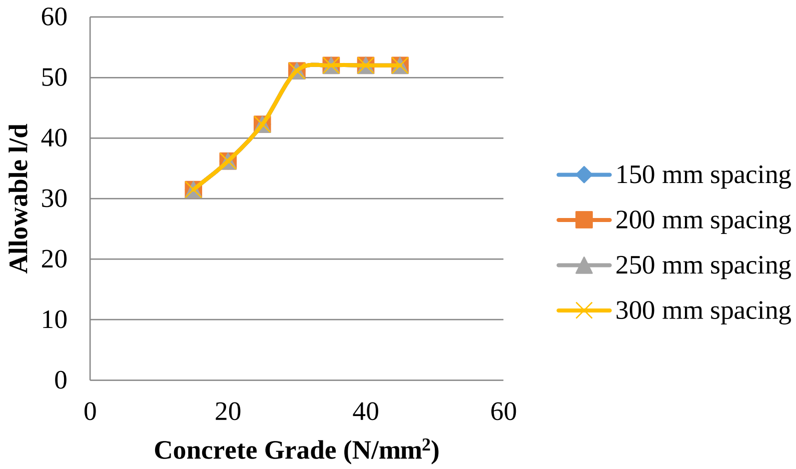

Figure 14: Variation of concrete grade with allowable l/d for 16 mm reinforcement for Slab C

From Figures 6 – 14, it was shown that only 10 mm reinforcement showed significant variation of slab thickness with concrete grade and deflections. This shows that when a smaller reinforcement is used in the slab, the variation of deflection with slab thickness would be critical and would need to be controlled but at higher reinforcement sizes (12 mm, 16 mm and possibly higher values), the variations is not significant and there may not be much need to control the deflection.

In Figure 6, there was a significant increase in the value of the allowable l/d when the concrete grade was changed from 15 to 20. As the compressive strength of the concrete was increased, the change in the values was less significant. Putting it as a percentage, there was a 19% increase in the deflection value which goes down to an average of 11% as the compressive strength was increased. These findings agree with the work of [9] and [15] that showed that increasing the compressive strength (concrete grade) of reinforced concrete beams or slabs leads to reduction in the deflection. For this slab too, the design fails the deflection check at concrete grade 15, 20 and 25.

The same trend continues in Slab B. However, when comparing the deflection value for both slabs at the same concrete grade, there was an average increase of 13%. In slab B, deflection failure occurred at concrete grade 15.

For Slab C, the values tend to become more stable (especially with lesser spacing) and the change negligible. The percentage difference between the 175 mm and 200 mm slab was approximately 12%. Deflection failure wasn’t prominent in this slab as it was for the other two. While there were deflection failures, it was primarily due to increasing reinforcement spacing.

3.1.2 Effect of Reinforcement Spacing and Size on the Deflection of Slab

Figures 15 - 17 shows the variation of concrete grade and spacing with the deflection of the slab. Only concrete grade 15 was used for this analysis because it was the only concrete grade that has the lowest and most critical values of allowable l/d ratio among all the 7 concrete grades used in the work.

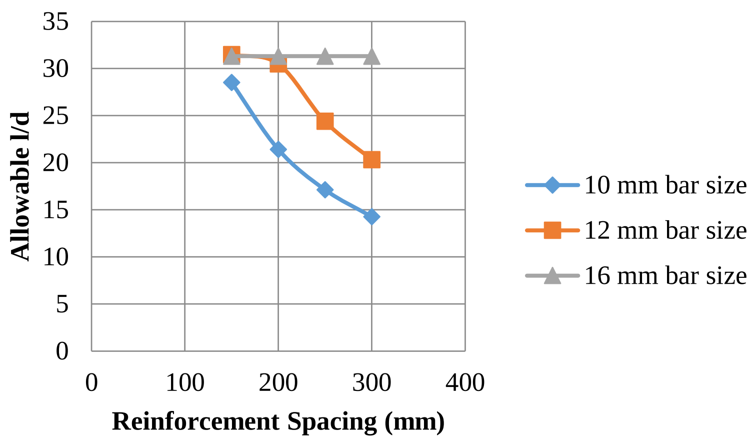

Figure 15: Variation of concrete grade with allowable l/d for 16 mm reinforcement

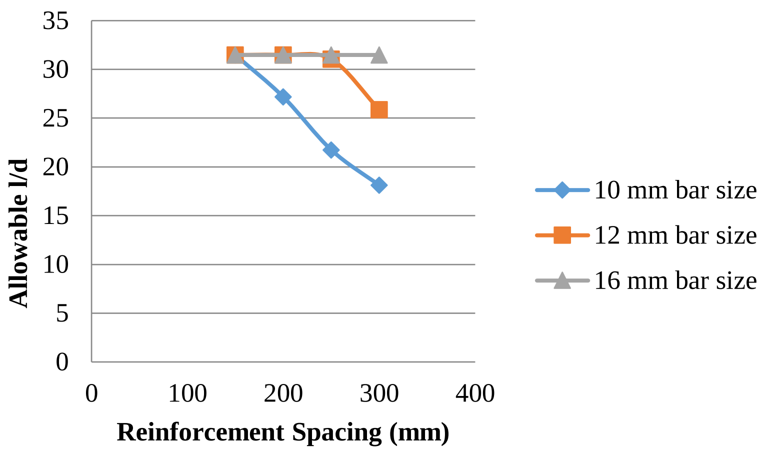

Figure 16: Variation of concrete grade with allowable l/d for 16 mm reinforcement

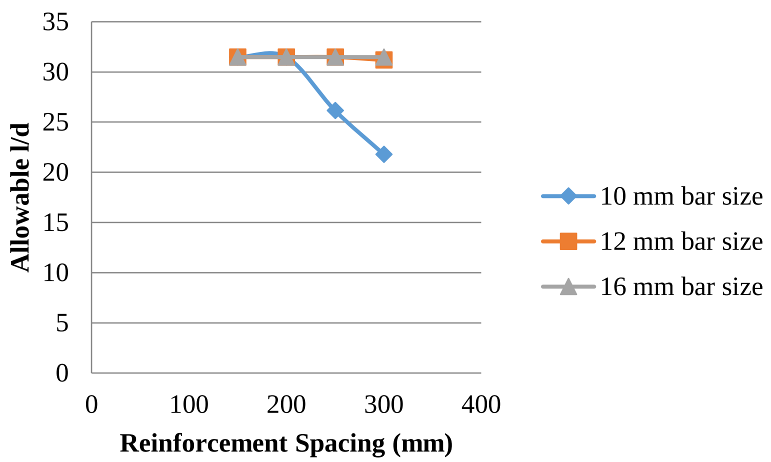

Figure 17: Variation of concrete grade with allowable l/d for 16 mm reinforcement

The behaviour of all the three slabs as regards bar spacing and size were the same. From Figures 15 - 17, increasing the spacing between bars leads to an equivalent decrease in the allowable l/d. In other words, the likelihood of failing the deflection check increases. On the other hand, increasing the size of the bars leads to an increment in the value of allowable l/d. The findings were in agreement with the work of [12] and [16] that showed that increasing bar size leads to increase in the value of allowable l/d which implies lower susceptibility to deflection. The deflection value also tends to be more stable/constant as the bar size increases.

3.2 Effect of Parametric Variations on the Crack Width of Slabs

Bending moment results in slab were used for the calculation of crack widths. Analysis of the slab was carried out in StaadPro to obtain the moments while the crack width computations were carried out in Tekla Tedds. For slab A, the bending moment obtained was 11.9 kN/m. For slab B, the bending moment was 11.8 kN/m while for slab C, the bending moment was 11.6 kN/m.

3.2.1 Effect of Variations of Concrete Grade and Reinforcement Spacing on the Crack Width of Slabs

Figures 18 – 26 shows the effects of variations of concreted grade and reinforcement spacing on the crack width of slabs.

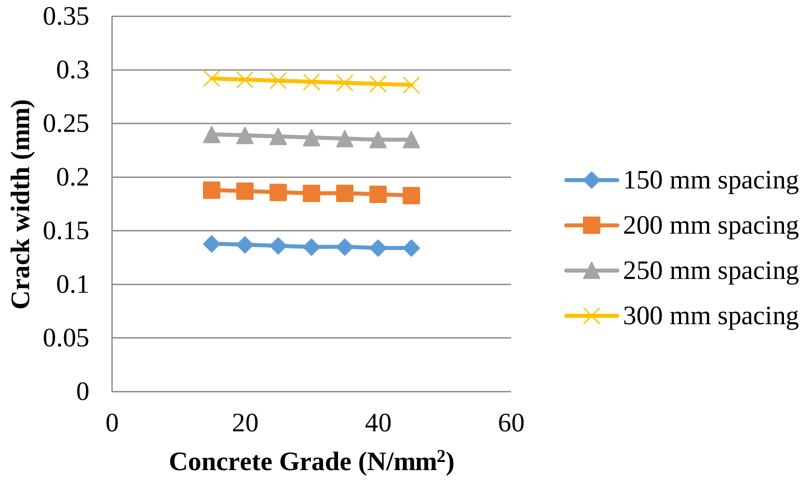

Figure 18: Variation of concrete grade with crack width for 10 mm reinforcement for Slab A

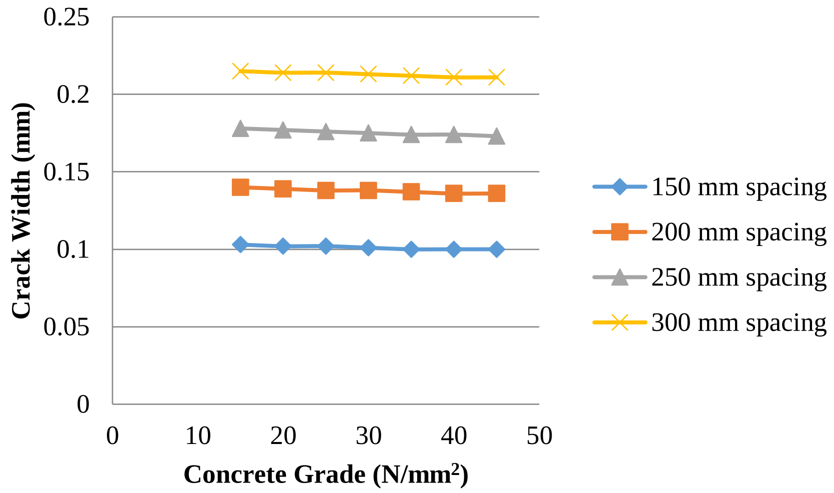

Figure 19: Variation of concrete grade with crack width for 12 mm reinforcement for Slab A

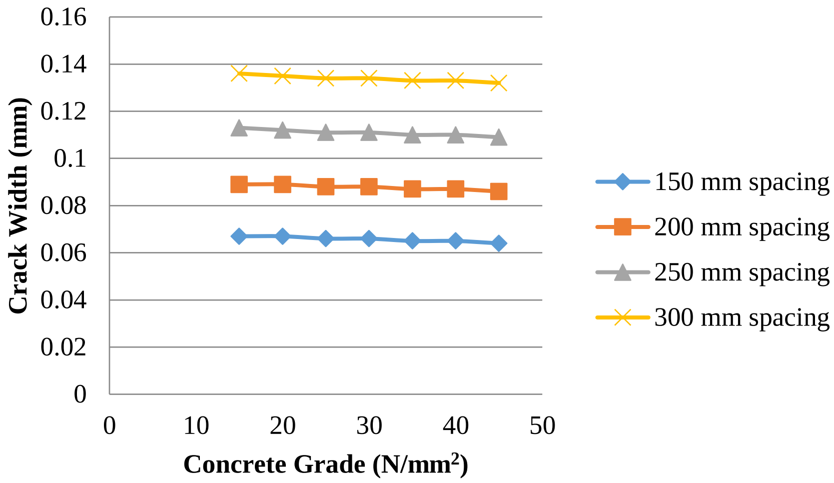

Figure 20: Variation of concrete grade with crack width for 16 mm reinforcement for Slab A

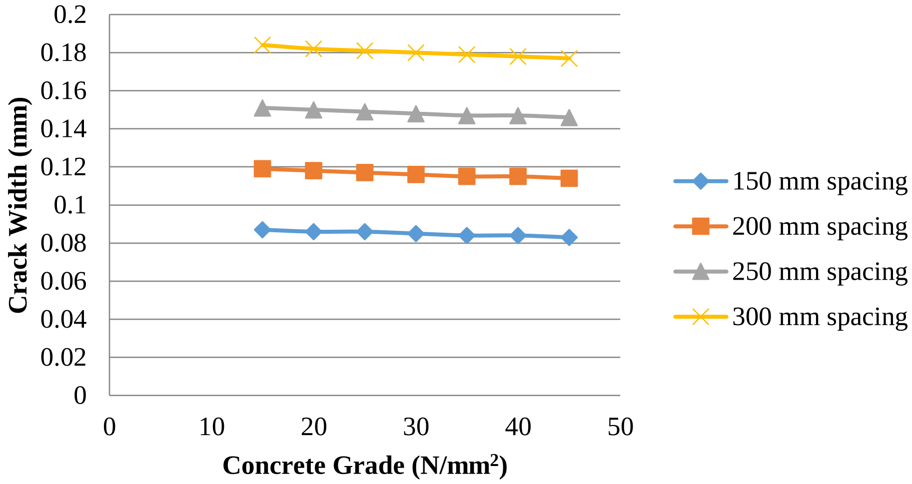

Figure 21: Variation of concrete grade with crack width for 10 mm reinforcement for Slab B

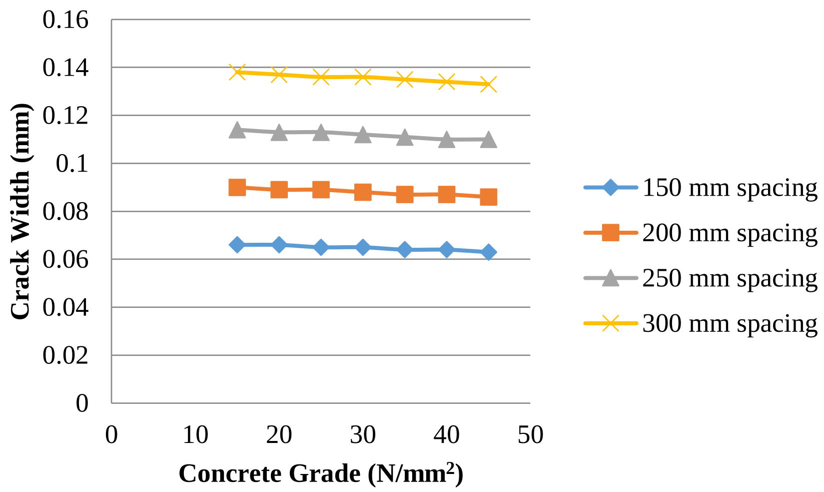

Figure 22: Variation of concrete grade with crack width for 12 mm reinforcement for Slab B

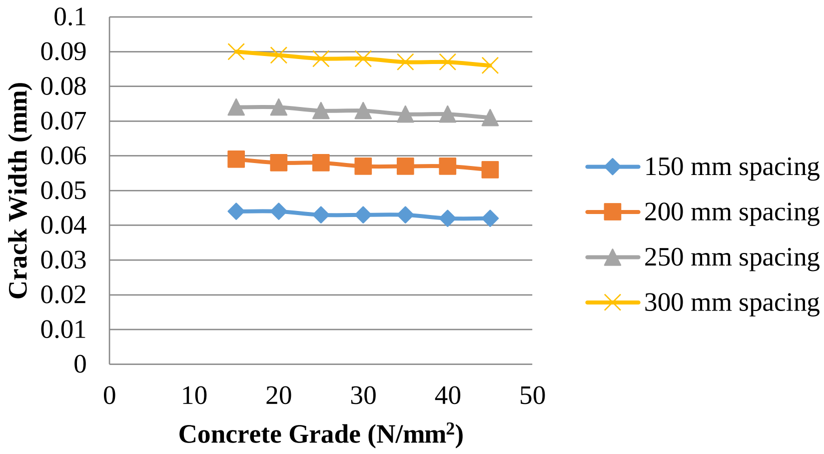

Figure 23: Variation of concrete grade with crack width for 16 mm reinforcement for Slab B

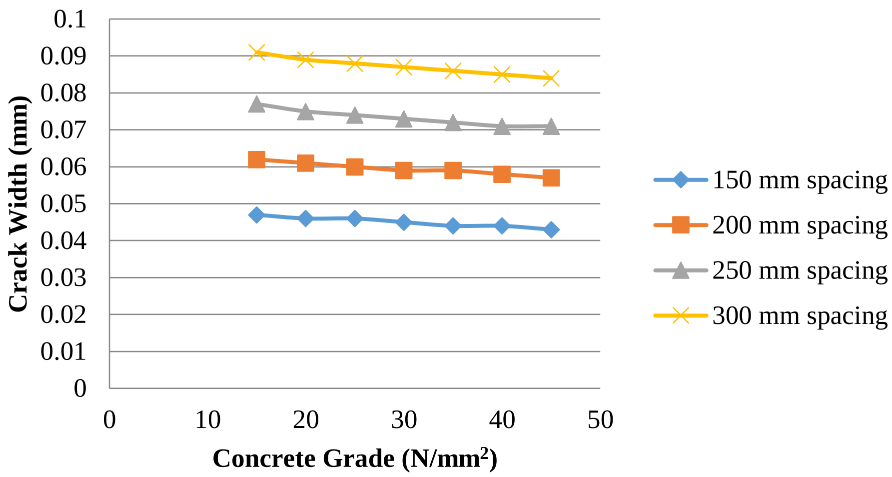

Figure 24: Variation of concrete grade with crack width for 10 mm reinforcement for Slab C

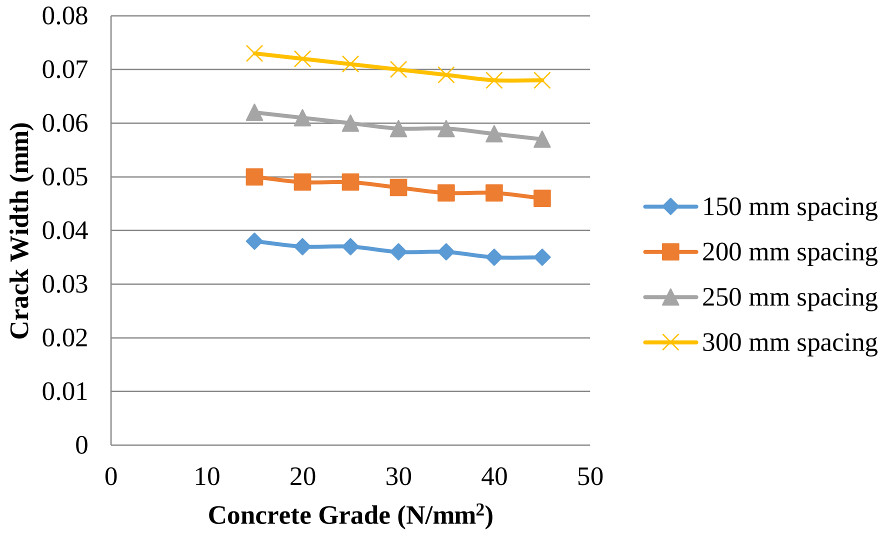

Figure 25: Variation of concrete grade with crack width for 12 mm reinforcement for Slab C

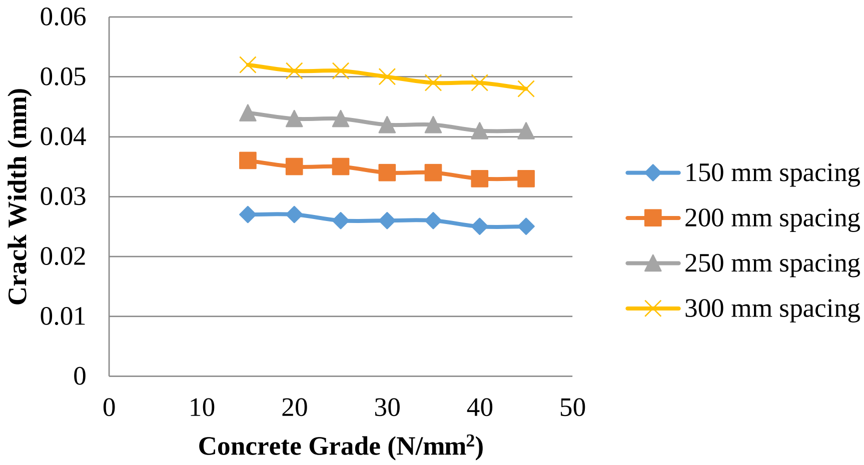

Figure 26: Variation of concrete grade with crack width for 16 mm reinforcement for Slab C

It can be seen from Figures 18 – 26 that the crack width only decreased slightly when the compressive strength of the concrete was increased. This decrease was applicable to slabs A, B and C. It was also observed that the crack width decreased with increase in reinforcement size, increase in slab thickness and reduction of the spacing of the slab. This was in agreement with the work of [10] and [17] that showed that increasing reinforcement size, increasing beam depth (slab thickness) and reducing reinforcement spacing reduces crack widths. The findings also agree with the work of [8] that showed that the thicker the slab, the smaller the crack width at the same load. The highest crack width of 0.292 mm was observed at concrete grade 15 of slab A at 10 mm reinforcement and 300 mm spacing while the lowest crack width of 0.025 mm was observed at concrete grade 45 of slab C at 16 mm reinforcement and 150 mm spacing. With the little change in crack width observed with the increase in concrete grade, the results agree with the study done by [9] that observed that concrete grade has little effect on the value of deflection and crack width.

3.2.2 Effect of Variations of Reinforcement Size and Spacing on the Crack Width of Slabs

Figures 27 - 29 shows the observed effects of variation of reinforcement size and spacing on the crack width of slabs. Concrete grade 15 only was used for this analysis because it produced the maximum crack width across all the concrete grades and also due the fact that same trend was observed across all the other concrete grades.

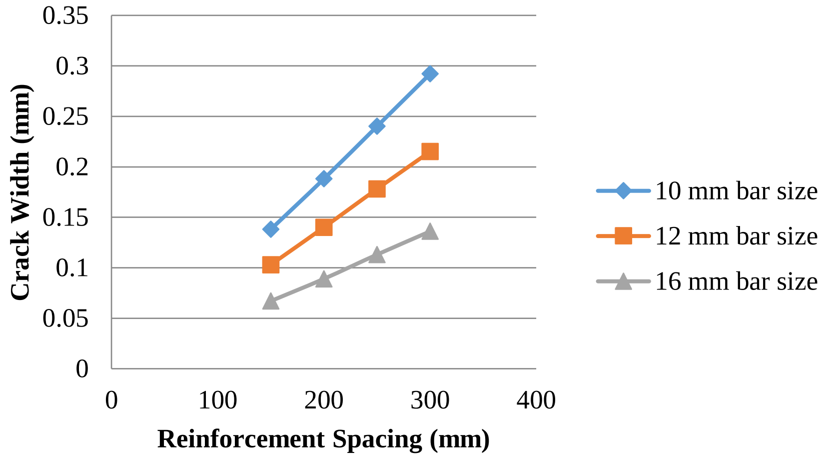

Figure 27: Variation of reinforcement size and spacing with crack width for concrete grade 15 – Slab A

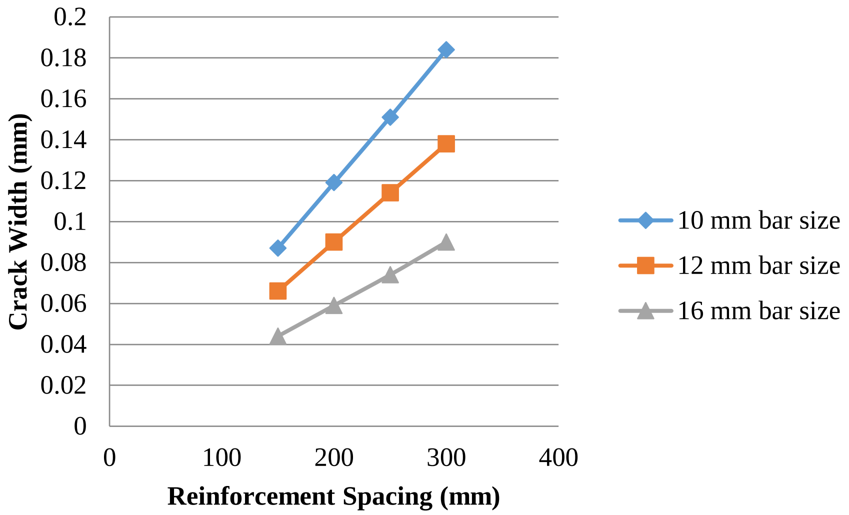

Figure 28: Variation of reinforcement size and spacing with crack width for concrete grade 15 – Slab B

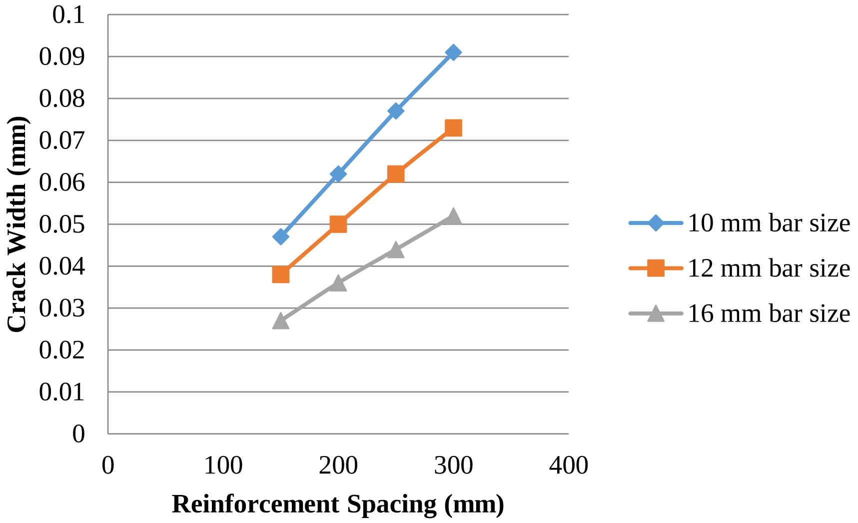

Figure 29: Variation of reinforcement size and spacing with crack width for concrete grade 15 – Slab C

From Figures 27 - 29, it was observed that the crack width becomes wider as the spacing between bars increases and becomes narrower as the diameter of the bar increases. This was in agreement with the work of [10] and [17] that observed in their study that when the reinforcement diameter is increased, the crack width is reduced. In slab A, as the bar spacing goes from 150 mm to 200 mm, from 200 mm to 250 mm and 250 mm to 300 mm, the crack width also increases by 36%, 27% and 21% respectively. The crack width decreases by 34% and 54% as the bar size increases from 10 mm to 12 mm and from 12 mm to 16 mm respectively.

In slabs B and C, the percentage increase and decrease in crack width are roughly similar. The result of this research agrees with the work of previous authors on related topics i.e. that bar size and spacing (amount of reinforcement) play a notable role in crack width control in reinforced concrete slabs.

4.0 Conclusion and Recommendations

4.1 Conclusion

The research was done to investigate the effects of concrete thickness on deflection and cracking in concrete slabs under varying design conditions. The following conclusions were made from the analysis of the results;

First, it was observed that as the thickness increases, the allowable l/d increases. This implies that the slab is less likely to fail deflection check at higher thickness. For cracking, as the concrete thickness increases, the crack width becomes smaller. However, from the analysis it was also observed that thickness affects crack width more than it does for deflection. Average increase in allowable l/d for different slabs was 13%. For the crack width, there was an average of 41% change in the values as the thickness was changed. Higher thickness of the slab also resulted in stable values for deflection and crack width despite changing parameters.

Secondly, it was discovered that concrete grade plays a much more significant role on deflection than it does on cracking. As was observed, the concrete grade caused an average of 17% increase in the allowable span/depth values. However, in the evaluation of the crack width, the maximum change brought upon by change in the compressive strength of concrete was just 0.8%. It was also found that the design failed the deflection checks at concrete grades 15, 20 and 25, however, the higher the thickness of the slab, the lower the propensity for failure.

Thirdly, it was shown that larger bars resulted in more acceptable values for both crack width and deflection. For deflection, larger bars resulted in stable deflection values despite the bar spacing.

Fourthly, it was also observed that increasing the spacing between bars was found to make slabs more susceptible to deflection and result in wider crack widths.

4.2 Recommendations

The following recommendations are made based on the research findings;

1. To aid in both deflection and crack control, a minimum of 12 mm bars and at most 250 mm spacing should be provided for slabs.
2. For residential buildings, a concrete grade of 25 and 30 can be used since the compressive strength has little effect on serviceability issues such as deflection and cracking. However, if a slab of 150 mm thickness is chosen, the concrete grade used should not be less than 30 N/mm^2. This is because lower concrete grades were found to be more susceptible to deflection in slabs of this thickness. The slab is also less likely to fail serviceability checks at higher concrete grades.
3. Though the effects of creep and shrinkage were not considered in the equations and formulas used for calculations, it is a well-known that they are among the properties of concrete that contribute to deflection and cracking in concrete slabs. It is recommended that this topic should be expanded to include the effects of creep and shrinkage in the calculations. In this way, more accurate deductions can be made on the behaviour of reinforced concrete slabs with respect to deflection and cracking.

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