How Efficient Is High Strength Concrete In Beams ?

ما هى كفاءة الخرسانة عالية المقاومة فى الكمرات ؟

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الملخص:

يستعرض هذا البحث دراسة تحليلية تهدف الى توضيح الفوائد والمميزات من استخدام الخرسانة عالية المقاومة فى الأعضاء الإنشائية المعرضة لعزم إنحناء مثل الكمرات. فعندما تزيد مقاومة الضغط للخرسانة المستخدمة فى الكمرات فإن محصلة قوى الضغط على قطاع الكمرة تزيد ومن ثم فإن حديد التسليح الطولى يتعرض إلى إنفعال زائد مما يؤدى الى حدوث شروخ أوسع بالخرسانة. ولذلك فمن الضرورى أن تزيد نسبة حديد التسليح فى القطاع لتحقيق إتزان القوى على مقطع الكمرة والإحتفاظ بنفس الإنفعال فى حديد التسليح وبالتالى تجنب حدوث شروخ أوسع بالخرسانة. ولقد وجد أن قيمة أقصى نسبة مسموحة لحديد التسليح (إجهاد الخضوع= ٣٦٠ ميجابسكال) تتغير من ٢,٤ إلى ٥,٤% عندما تتغير مقاومة الخرسانة من ٢٥ الى ٧٥ ميجابسكال. وللحصول على نفس مستوى التسليح للكمرات المصنوعة من خرسانة ذات مقاومات مختلفة فإن نسبة حديد التسليح المستخدمة فى كل كمرة ينبغى أن تكون نسبة ثابتة من قيمة أقصى نسبة مسموحة لحديد التسليح فى تلك الكمرة. ونتيجة لزيادة نسبة الحديد فى الكمرات المصنوعة من خرسانة عالية المقاومة فإن السعة التحميلية لها تزيد. وفى المتوسط فقد وجد أن السعة التحميلية للكمرة تتضاعف مرتين عندما تزيد مقاومة الضغط للخرسانة المستخدمة مرتين ونصف. ومن ناحية أخرى فإن إستخدام الخرسانة عالية المقاومة فى الكمرات التى لها نفس درجة التسليح والمعرضة لنفس عزم الإنحناء يؤدى إلى الحصول على قطاع أصغر للكمرة وبالتالى تخفيض الوزن الذاتى للكمرة. على سبيل المثال فإن مساحة مقطع الكمرة يقل إلى حوالى ٤٠% من مساحة المقطع الأصلىعندما تزيد مقاومة الضغط للخرسانة المستخدمة ثلاثة مرات. ويقدم هذا البحث المعادلات والرسومات البيانية التى تتيح لمستخدمها إمكانية إجراء التخفيض المناسب على القطاع الخرسانى نتيجة إستخدام الخرسانة عالية المقاومة. فمثلاً من الممكن أن يتم التخفيض فى عرض القطاع أو فى عمقه أو أن يتم التخفيض فى كل من العرض والعمق معاً حتى يتم إستيفاء حدود التشغيل المطلوبة.

Abstract .. The paper presents an analytical study to clarify the benefits and.the advantages of using high strength concrete in members subject to flexure; e.g., beams. When high strength concrete is used in beams, the reinforcement ratio (μ) should increase to insure the equilibrium of forces on the cross section, to avoid excessive strains of steel reinforcements and hence, to provide the same level of reinforcement (μ/μ_{max} = constant). Accordingly, the load carrying capacity of the beam increases significantly. The use of high strength concrete in a beam with a given reinforcement level results in significant reduction and saving of concrete mass. This reduction may be in the beam depth or in the beam breadth or in both of them

Keywords .. High Strength Concrete, Beams, Reinforcement Ratio, Ductility.

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1. INTRODUCTION

The progress of concrete technology and the increasing use of high strength concrete (HSC) becomes fairly common worldwide. However, the economic benefits of using HSC are fully apparent and outweigh significantly the increased costs of raw materials and quality control. Some studies concerning the advantages and the economic benefits of using HSC in columns have been reported [4-6]. To the authors' knowledge, such studies for members subjected to flexure; e.g., beams are not so far found.

In most of the design methods of reinforced concrete structures, the tensile strength of concrete is generally neglected and steel reinforcements take charge of carrying the entire applied tension. For instance, in members subjected to bending such as beams, the role of concrete is limited in the zone above the neutral axis. Concrete mass in this part is normally less than 50% of the used concrete quantity. The rest of concrete ($\geq$ 50%) lies under tension and is neglected in design. Consequently, some engineers may argue that the use of HSC in beams is not beneficial enough compared to the case of members subject to axial compression such as columns. Fortunately, this idea is not exactly correct. It is found that, the use of HSC in beams is effective and provides a lot of benefits.

When concrete with higher strength is used in a beam with a given area of cross section and a given reinforcement level (μ/μ_{max}=constant), the load carrying capacity of the beam increases significantly. The reason is that, when the concrete strength increases, the compressive force resultant on the cross section increases as well. To insure the equilibrium of forces on the beam cross section, and to avoid excessive steel strain and wide crack width, it becomes necessary to use higher reinforcement ratio. Hence, the load carrying capacity increases. However, this analytical study presents an attempt to clearly show the benefits and the advantages of using HSC in beams.

2. OBJECTIVE

The objective of this paper is to analytically study the benefits and the advantages of using HSC in members subject to flexure such as beams. The objective is not to provide full design and dimensions of beams, but it is to encourage engineers to use HSC not only in columns but also in beams and in all structural members alike.

3. STRENGTH DESIGN METHOD

The current Egyptian Code for design and construction of reinforced concrete structures is vai:. and applicable for concrete with compressive strength not more than 40 MPa[3]. The code does not include any consideration for concrete with higher strength. Therefore, the American Building Code [ACI 318-95] is accepted in this study. In the strength design method adopted by the ACI Building Code[1], beams are designed to have a design strength at all sections at least equal to the required strength calculated for the applied loads and forces. The design strength is computed by multiplying the "nominal strength" by a strength reduction factor (ϕ<1). For flexure without axial load, the strength reduction factor is assumed to be 0.9 The required strength is computed by multiplying the service loads by a load factor ($\gamma > 1.0$). Hence, the margin of safety is provided by both two factors γ and ϕ. Strains in reinforcement and concrete are assumed to be proportional to the distance from the neutral axis. The stress in reinforcement is proportional to the strain below the yield strength (f_y). For strains greater than that corresponding to f_y, stress is considered independent of strain and equal to f_y. The maximum strain at extreme concrete compression fibres is assumed equal to 0.003. Although this value is not conservative for HSC, it represents satisfactorily the experimental results of HSC [2]. The rectangular stress distribution as shown in Fig. 1 is accepted in the American Code for HSC. The ratio (β=a/c) between the depth of concrete stress block (a) and the depth of neutral axis (c) is taken as 0.85 for concrete with cylinder strength up to 30 MPa. For strengths between 30 and 55 MPa, β is reduced at a rate of 0.008 for each 1 MPa of strength in excess of 30 MPa but β should not be taken less than 0.65 for concrete strengths greater than 55 MPa.

4. REINFORCEMENT LEVEL

The ductility of a singly reinforced concrete beam is mainly depending on concrete strength, steel yield strength, and the ratio of steel reinforcement in the cross section of concrete. The interaction between these three main parameters govern the ductility level of a reinforced concrete beam. However, a balanced strain condition exists at a cross section when the maximum strain at the extreme compression fibres just reaches 0.003 simultaneously with the first yield strain ($\varepsilon_y = f_y/E_s$) in the tension reinforcement. The reinforcement ratio at this condition is called μ_b. When the longitudinal steel ratio increases beyond μ_b, a crushing of concrete is expected (brittle failure). In order to attain a level of ductile behaviour of concrete beams and to avoid failures by crushing of concrete in the compression zone, a maximum longitudinal reinforcement ratio (μ_{max}) should be specified. A value of 0.75 μ_b is recommended by the ACI Building Code[1] for the maximum reinforcement ratio. This limitation provides sufficient ductile behaviour in normal cases of design. Accordingly, the reinforcement level can be expressed in terms of μ/μ_{max}

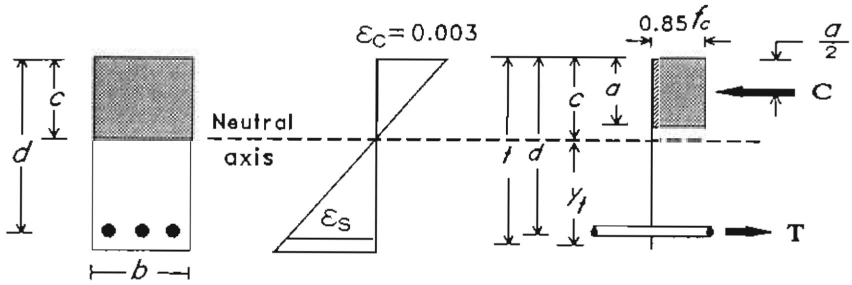


Fig. 1 Rectangular reinforced concrete beam at ultimate moment.

The equilibrium of forces (Fig. 1) yields: $A_s f_y = 0.85\ f_c\ a\ b$

$$\frac{a}{d} = \frac{\mu\ f_y}{0.85\ f_c} \qquad (1)$$

From the strain diagram in Fig. (1): $\frac{c}{d} = \frac{\varepsilon_c}{\varepsilon_c + \varepsilon_s} = \frac{0.003}{0.003 + \varepsilon_s}$

but:

$$\frac{a}{d} = \left(\frac{a}{c}\right)\left(\frac{c}{d}\right) = \beta\left(\frac{c}{d}\right) = \frac{0.003\,\beta}{0.003 + \varepsilon_s} \qquad (2)$$

where: $\beta = 0.85$ $f_c \leq 30$ MPa

$\beta = 0.85 - 0.008\ (f_c - 30)$ $30 \leq f_c \leq 55$ MPa

$\beta = 0.65$ $f_c \geq 55$ MPa.

Equations (1)and (2) give:

$$\frac{\mu\ f_y}{0.85\ f_c} = \frac{0.003\ \beta}{0.003 + \varepsilon_s} \qquad (3)$$

at the balanced condition; $\mu = \mu_b$, $\varepsilon_s = \varepsilon_y$, $E_s = 200{,}000\ MPa$

$$\mu_b = \left(\frac{510}{600 + f_y}\right)\left(\frac{f_c}{f_y}\right)\beta \qquad (4)$$

$$\mu_{max} = 0.75\mu_b = \left(\frac{382.5}{600 + f_y}\right)\left(\frac{f_c}{f_y}\right)\beta \qquad (5)$$

Comparing two different beams at a given yield strength of steel reinforcement:

$$\frac{\mu_{max\,2}}{\mu_{max\,1}} = \left(\frac{\beta_2}{\beta_1}\right)\left(\frac{f_{c2}}{f_{c1}}\right) \qquad (6)$$

at a constant level of reinforcement: $\frac{\mu_2}{\mu_{max\,2}} = \frac{\mu_1}{\mu_{max\,1}}$ = constant

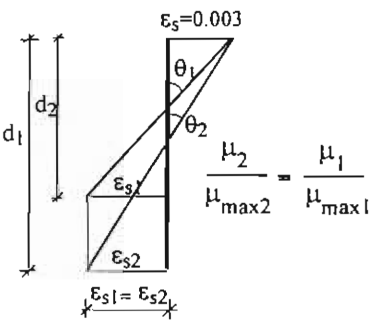


Fig. 2 Strain of Steel Reinforcement at a Given Reinforcement Level.

then:

$$\frac{\mu_2}{\mu_1} = \frac{\mu_{max2}}{\mu_{max1}} = \frac{\beta_2 f_{c2}}{\beta_1 f_{c1}} \tag{7}$$

applying equation (3) for two beams at a given reinforcement level:

$$\frac{\varepsilon_{s1} + 0.003}{\varepsilon_{s2} + 0.003} = \frac{\beta_1 f_{c1} \mu_2}{\beta_2 f_{c2} \mu_1} \tag{8}$$

substituting for μ_2/μ_1 in equation (8), then: $\varepsilon_{s1} = \varepsilon_{s2}$ (9)

When a concrete with higher strength is used in a beam, the resultant of the compressive force on the cross section increases and steel reinforcements are more likely to suffer excessive strains and hence wider cracks are expected. Thus, to insure a favorable strain with acceptable crack width in HSC beams, steel ratio in the cross section should increase. Equations (5) through (9) show that, when the steel ratio in beams with different compressive strengths is chosen as a constant fraction of the maximum allowable ratio (μ/μ_{max}=constant), the same steel strain in all beams is obtained (Fig. 2). In addition, the width of crack in different beams becomes approximately equal. Fig. 3 shows the effect of concrete grade on the maximum allowable reinforcement ratio in beams with rectangular cross section. Equation (5) is applied for different strength values of concrete and steel. For 20 MPa concrete and for steel with yield strength of 500, 360, and 240 MPa, the maximum reinforcement ratio are 1.2, 1.9, and 3.2% respectively. When concrete strength increases, the maximum ratio of steel increases significantly. For 60 MPa concrete, the maximum allowable steel ratio becomes 2.7, 4.3, and 7.4% respectively. Thus, the increase of concrete strength from 20 to 60 MPa results in a corresponding increase of the maximum reinforcement ratio with about 130%.

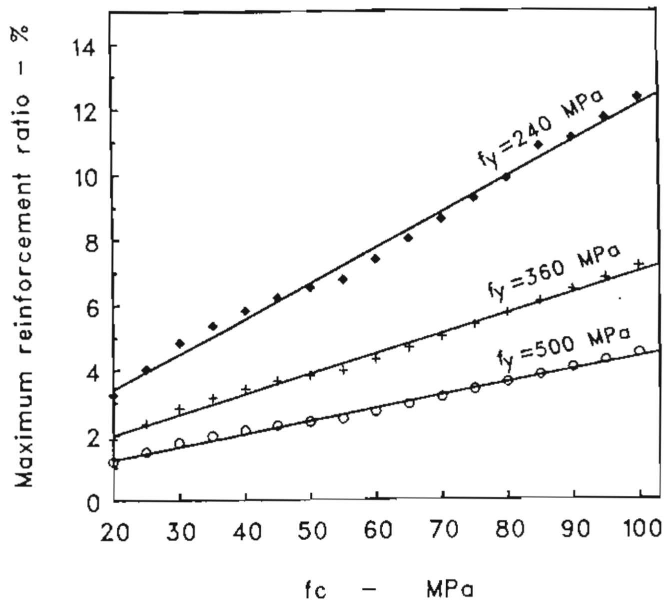


Fig.3 Effect of concrete strength on the maximum reinforcement ratio.

5. EFFECT OF CONCRETE STRENGTH

5.1 Load-Carrying Capacity

The equilibrium of forces in Fig.1 yields the following equation for computing the nominal flexural strength of a beam with rectangular cross section:

$$M_{fl} = \mu\, bd f_y \,(d - \frac{a}{2})$$

where: $a = \mu\, bd\, f_y / 0.85\ b\ f_c$

f_c is the compressive strength of concrete cylinder.

hence,
$$M_{fl} = \mu\, bd^2 f_y \,(1 - \frac{\mu f_y}{1.7 f_c}) \tag{10}$$

when the concrete strength increases from f_{c1} to f_{c2} in a beam with a given cross section area (bd), then the ultimate moment changes from M_{fl1} to M_{fl2} as:

$$\frac{M_{fl2}}{M_{fl1}} = \frac{\mu_2 \,(1 - \frac{\mu_2 f_y}{1.7 f_{c2}})}{\mu_1 \,(1 - \frac{\mu_1 f_y}{1.7 f_{c1}})} \tag{11}$$

for the same level of reinforcement; $\mu_1/\mu_{max1} = \mu_2/\mu_{max2} = c$; $c \leq 1\ 0$

substituting for μ_1 and μ_2 in equation (11),

$$\frac{M_{fl2}}{M_{fl1}} = (\frac{f_{c2}}{f_{c1}})\ (\frac{\beta_2}{\beta_1})\ (\frac{600 + f_y - 225\ c\ \beta_2}{600 + f_y - 225\ c\ \beta_1})$$

$$M^r = \frac{f^r}{\lambda^2} \tag{12}$$

where M^r is the relative flexural moment $= M_{fl2} / M_{fl1}$

f^r is the relative concrete strength $= f_{c2} / f_{c1}$

$$\lambda = \sqrt{(\frac{\beta_1}{\beta_2})\ (\frac{600 + f_y - 225\, c\, \beta_1}{600 + f_y - 225\, c\, \beta_2})} \tag{13}$$

Equation (12) presents the effect of the change of concrete strength on the loading capacity of a beam in a dimensionless form. It is worth noting that the parameter λ in equation (12) has a small effect on the loading capacity. When the concrete strength changes from 30 MPa or less to a value of 55 MPa or more, the value of λ becomes constant for a given yield strength. However, the effect of steel yield strength on the value of λ is very small and can be neglected. For instance, steel yield strength of 240, 360, and 500 MPa results in a parameter λ value of 1.106, 1.111, and 1.116 respectively. Thus an average value of 1.11

can be adopted for the parameter λ regardless of the yield strength value. Equation (12) shows that the value of the relative moment (M_{fl2}/M_{fl1}) is reversely proportional to the square value of λ. Thus, the parameter λ has a reversal effect of about 20% on the relative moment. On the other hand, the relative moment is directly proportional to the relative strength of concrete (f_{c2}/f_{c1}). Fig. (4a) presents the relationship between the relative moment and the relative strength of concrete. On average, when the concrete strength is fourfold (e.g., from 20 to 80 MPa), the loading capacity increases 3.24 times. This means that, the span of a beam with a given cross section can be increased to 1.8 times when the concrete strength increases four times.

A practical example for the effect of concrete strength on the load carrying capacity is shown in Fig. (4b). Suppose we have a beam with a given cross section (300x950 mm^2) and concrete strength is changed from 20 to 80 MPa. Two cases of the beam calculations should be distinguished. In the first case, the beam is assumed with a given area of steel in the cross section (e.g., A_s=6000 mm^2) regardless of the reinforcement level at different concrete strength. In this case, only 21.5% increase of the moment capacity is obtained. However, the level of reinforcement ($c=\mu/\mu_{max}$) is lowered from 0.95 to 0.31 and steel strain increased from 2.7 to 14.5 ‰ (i.e., the strain increased 5.4 times).

In the second case of calculations, the beam is assumed with a given reinforcement level at different concrete strengths, i.e., the ratio μ/μ_{max} is kept constant regardless of the used area of steel. In this case a significant increase of the flexural moment is achieved. When the μ/μ_{max} is adopted as 0.75, the moment increases with more than 220%. This increase of moment is associated with a corresponding increase of the used area of steel (≈206%) but the strain of reinforcement is kept constant at 5.5‰.

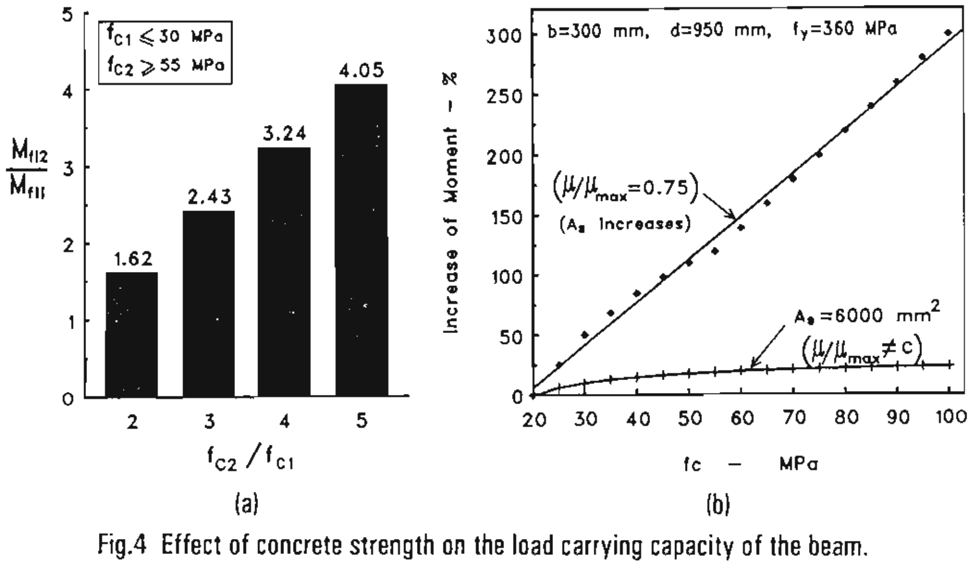


Fig.4 Effect of concrete strength on the load carrying capacity of the beam.

5.2 Beam Depth

The effect of concrete strength on the depth of a beam with a given breadth is studied. The beam is subjected to a given factored moment ($\phi M_{f1} = 0.9\ M_{f1}$) and the level of reinforcement is kept constant. when the concrete strength increases from f_{c1} to f_{c2}, then the beam depth changes from d_1 to d_2 as:

$$\phi M_{f1} = \mu_1\ b d_1^2\ f_y\ (1 - \frac{\mu_1\ f_y}{1.7\ f_{c1}}) = \mu_2\ b d_2^2 f_y\ (1 - \frac{\mu_2\ f_y}{1.7\ f_{c2}}) \qquad (14)$$

$$\frac{d_2}{d_1} = \sqrt{\frac{f_{c2}}{f_{c1}}}\ \sqrt{\frac{\mu_1 (1.7 f_{c1} - \mu_1 f_y)}{\mu_2 (1.7 f_{c2} - \mu_2 f_y)}} \qquad (15)$$

for the same level of reinforcement; $\mu_1/\mu_{max1} = \mu_2/\mu_{max2} = c$

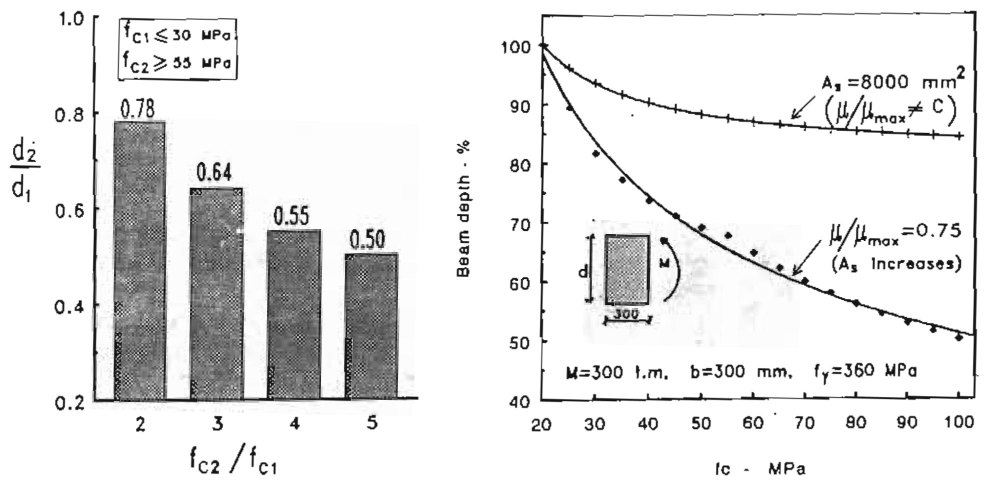
where c and μ_{max} are defined previously.

substituting for μ_1 and μ_2 in equation (15), then:

$$d^r = \frac{\lambda}{\sqrt{f^r}} \qquad (16)$$

where d^r is the relative beam depth = d_2/d_1

λ and f^r are defined in equation (13).



(a) (b)

Fig. 5 Effect of concrete strength on the beam depth.

It is previously shown that, the parameter λ is slightly affected by the change of steel yield strength and it normally lies in the vicinity of 1.11 regardless of the yield strength. Thus, for a given reinforcement level, the relative beam depth (d_2/d_1) is almost independent on the steel yield strength but is dependent on the relative concrete strength (f_{c2}/f_{c1}). Fig. (5a) shows the relationship between the relative beam depth and the relative concrete strength. It can be noted that, when concrete strength is doubled, the beam depth is reduced by about 22%. The beam depth reaches half the initial depth when the concrete strength is fivefold. It is worth noting that, the design for a given reinforcement level results in the same steel strain whatever the concrete strength is (see equation 9 and Fig 2).

Suppose we have a beam subjected to a factored bending moment of 3000 kN.m (≅ 300 t.m), the beam breadth is 300 mm, the yield strength of steel is 360 MPa. In the first design method, a constant area of steel of 8000 mm^2 is adopted regardless of the reinforcement level. The concrete strength changes from 20 to 80 MPa. The solution for f_c = 20 MPa gives a depth of 1440 mm and μ/μ_{max} equals 0.98. For f_c = 80 MPa, the depth becomes 1228 mm (15% reduction), while μ/μ_{max} reaches 0.38. However, steel strain changes from 3.5 to 14 (i.e., the crack width is almost fourfold).

The foregoing example is recalculated considering a constant reinforcement level in both cases (e.g., $\mu_1/\mu_{max1} = \mu_2/\mu_{max2} = 0.75$). For concrete strength of 20 MPa, the required depth is 1604 mm and the area of steel equals 6788 mm^2. When the concrete strength increases to 80 MPa, the beam depth becomes 898 mm (i.e., 56% of the initial depth), while steel area increases to 11635 mm^2 (i.e., 71% increase). For both cases, the strain is equal to 3.4 . This example (Fig. 5b) indicated that, the effect of concrete strength on the beam depth is greatly dependent on whether the design is based on a given area of steel or a given reinforcement level ($\mu = c\,\mu_{max}$). If a beam depth is calculated for a given area of steel, then the effect of concrete strength on the beam depth is not considerable. Whereas, if the beam depth is calculated for a given reinforcement level, (i.e., μ/μ_{max} = constant), a considerable reduction of the depth is attained.

5.3 Beam Breadth

When the concrete strength changes from f_{c1} to f_{c2} in a beam with a given depth (d) and subject to a given factored moment ($\phi M_{f1} = 0.9\, M_{f1}$), the beam breadth changes from b_1 to b_2. The ratio (b_2/b_1) can be calculated by a manner similar to that in section 5.2:

$$\frac{b_2}{b_1} = \left(\frac{\mu_1}{\mu_2}\right)\left(\frac{f_{c2}}{f_{c1}}\right)\left(\frac{1.7\,f_{c1} - \mu_1\,f_y}{1.7\,f_{c2} - \mu_2\,f_y}\right) \tag{17}$$

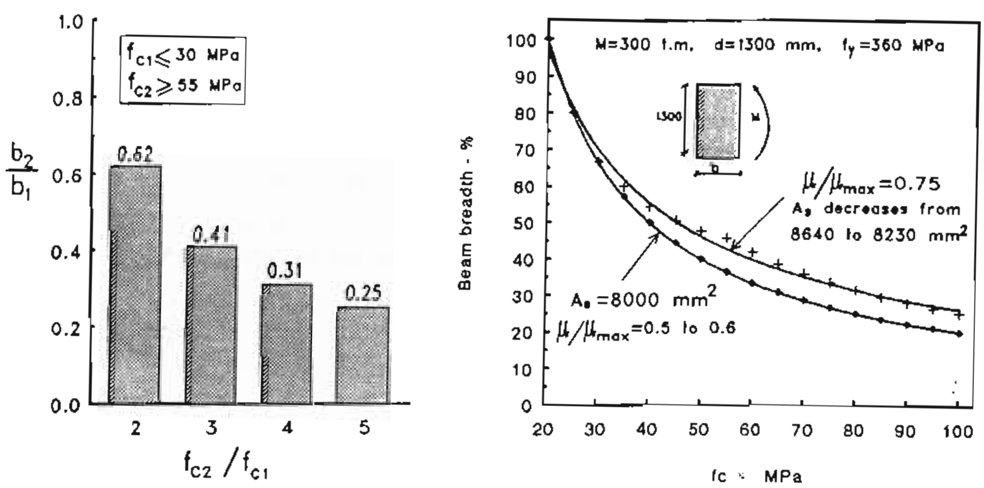
where μ_1 and μ_2 are the reinforcement ratios in case of concrete strength f_{c1} and f_{c2} respectively. after substituting for μ_1 and μ_2 in equation (17), the relative beam breadth (b_2/b_1) can be derived as:

$$b^r = \frac{\lambda^2}{f^r} \tag{18}$$

where b^r is the relative beam breadth = b_2/b_1

λ and f^r are defined in equation (13).

Equation (18) indicates that, the relative beam breadth is reversely proportional to the relative concrete strength. Thus, the effect of concrete strength is more pronounced on beam breadth compared to beam depth (Equation 16). For instance, when concrete strength is doubled, the breadth of a beam reaches 62% of its initial breadth as shown in Fig. (6a). Whereas, when concrete strength increases four times, the relative beam breadth (b_2/b_1) becomes only 31%. As a practical example, suppose we have a beam subjected to a factored bending moment of 3000 kN.m (≈300 t.m), the beam depth is 1300 mm, and the yield strength is 360 MPa. The beam is calculated at a given reinforcement level (μ/μ_{max}=0.75) regardless of the used steel area. In this condition, a beam breadth of about 54, and 31% can be obtained when concrete with strength of 40 and 80 MPa is used in lieu of 20 MPa. In addition, the used steel area is less with 2 to 4% but an equal strain is achieved in all cases (ε_s=5.5‰). Fig. (6b) presents another condition of calculation for the same beam. A given steel area of 8000 mm^2 is assumed regardless of the reinforcement level. Thus, for 20 MPa-concrete, a breadth of about 600 mm is required (μ/μ_{max}=0.55, ε_s=8.6‰). If a concrete with strength of 40 MPa is used, a 300 mm breadth is sufficient (μ/μ_{max}=0.61, ε_s=7.5‰). This means that 50% of concrete mass can be saved if we use concrete with strength of 40 MPa instead of 20 MPa. When 80 MPa-concrete is used a breadth of 150 mm only is sufficient and a saving of 75% of concrete quantity is achieved (μ/μ_{max}=0.72, ε_s=5.9‰). This may give a decisive answer to the question: How efficient is HSC in beams?



(a) (b)

Fig. 6 Effect of concrete strength on the beam breadth.

5.4 Breadth - Depth Interaction

It may be argued that, if the advantage of using HSC is taken entirely as a full reduction in the beam depth, inadequate stiffness that may adversely affect the serviceability of a structure may result in. In such a respect, it could be possible to make the full reduction in the beam breadth or to make a partial reduction in both depth and breadth. When the concrete strength of a beam changes from f_{c1} to f_{c2}, the dimensions of the cross section change from b_1 and d_1 to b_2 and d_2. However, the values of b_2 and d_2 can be similarly calculated by a manner like that in the previous sections and the following equation can easily be concluded:

$$\left[bd^2\right]^r = \frac{\lambda^2}{f^r} \tag{19}$$

where $[bd^2]^r$ is the relative cross section dimension = $(b_2\, d_2^{\,2})/(b_1\, d_1^{\,2})$

λ and f^r are as defined in equation (13).

However, the comparison between equation (16) and equation (18) shows that when the concrete strength increases, the beam breadth is affected by a rate equals the square value by which the beam depth is affected. Fig 7 shows the solution of equation (19) for different values of beam depth and beam breadth. This allows several possibilities for the solution of a beam at a given reinforcement level. For example, when the concrete strength increases three times, it becomes possible to choose the same breadth and a depth with about 64% of its initial value. Otherwise, both the depth and the breadth can be reduced to about 91 and 50% of their initial values, respectively.

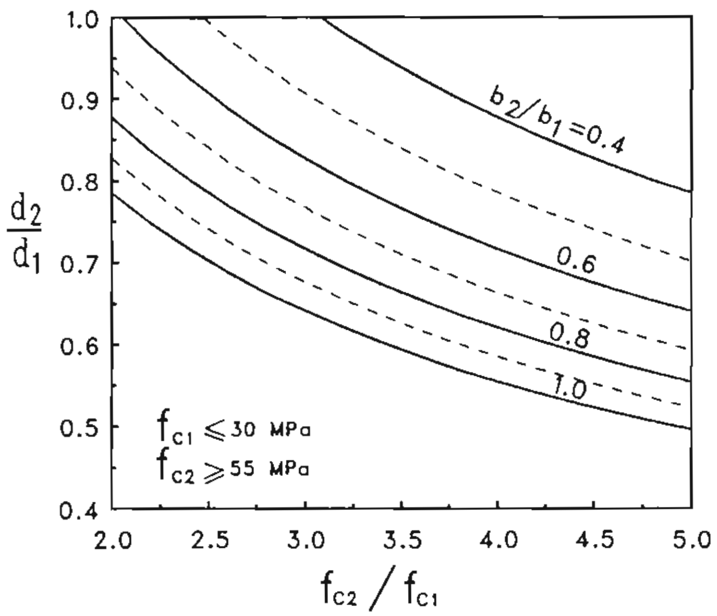


Fig. 7 Effect of concrete strength on both beam depth and breadth.

The interaction between the depth and the breadth permits the calculation of the relative cross-section area of a beam (A_2/A_1). The ratio A_2/A_1 equals the relative concrete volume (V_2/V_1) and hence represents the relative concrete mass (W_2/W_1). Fig.8 shows the relationship between the relative concrete strength and the relative area of the beam cross-section. It can be noted that, the reduction of the area is optimized when the benefit of HSC is taken entirely as a full reduction in the beam breadth. For instance, at f_{c2}/f_{c1} equals three, the cross-section area of the beam reaches to about 40% of its initial value when the breadth is reduced to 40% but the depth does not change. Whereas, the area becomes about 64% of its initial value when the breadth does not change but the depth is reduced to 64% of the initial depth (f_{c2}/f_{c1}=3). Accordingly, the designer should compromise to meet the requirements of the serviceability as well as the strength.

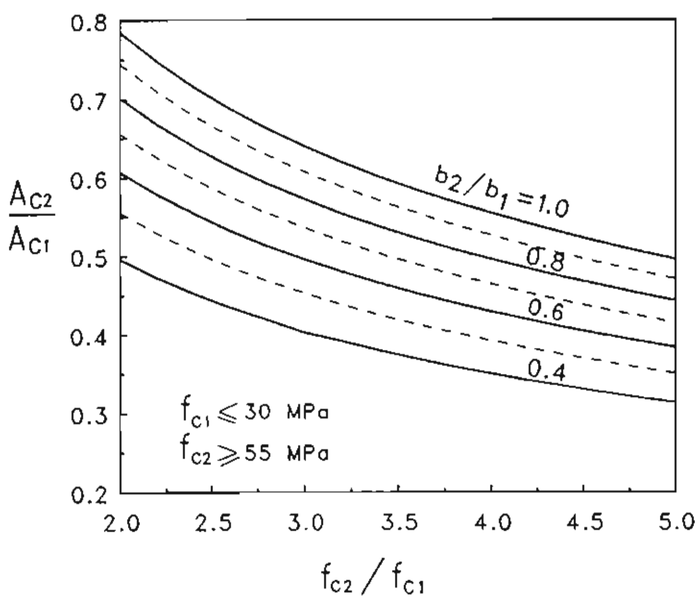


Fig. 8 Effect of concrete strength on the area of the beam cross section.

6. CONCLUSIONS

Within the scope of this study, the following conclusions are drawn:

1- When HSC is used in beams, the reinforcement ratio (μ) increases to insure the same level of reinforcement (μ/μ_{max}=constant) and to avoid excessive steel strain and wider crack width. Thus, the load carrying capacity of the beam increases significantly. On average, the load carrying capacity of a beam is doubled when the concrete strength increases 2.5 times.

2- The use of HSC in a beam with a given reinforcement level is beneficial, it allows smaller cross sections, and provides significant reduction and saving in concrete mass. For example, the concrete mass of a beam can be reduced to about 40% of its initial mass when the concrete strength increases three times.

3- The interaction between beam depth and beam breadth is presented in a graphical form Several solution possibilities are available to allow the user to meet the requirements of strength and serviceability. It could be possible to make a full reduction in either beam depth or breadth or to make a partial reduction in both of them. For example, when the concrete strength changes from 20 to 60 MPa, about 59% reduction in the beam breadth or 36% reduction in the beam depth can be achieved. Another solution possibility is obtained by making the reduction as 20% in the depth and 35% in the breadth.

4- The use of concrete with higher strength in a beam without changing the area of steel in the cross section results in a relatively small reduction of the beam depth but it results in a considerable reduction in the beam breadth.

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