TECHNICAL PAPER

How is the dosage of macro synthetic fibers determined in slab on ground applications

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Burak graduated from Dicle University in 2009, ranking first in his department. He completed master's degree form YILDIZ Technical University in 2011. He completed his thesis subject properties of concrete containing polypropylene fiber produced with recycled aggregate on fiber reinforced concrete. He has been continuing his studies on fiber and concrete since 2009.

Samed graduated from Istanbul Technical University in 2014. He continues master's degree form BILECIK University. He took part dometic and abroad projects. Since 2020, He has been working as Technical Manager at Polyfibers.

KEYWORDS

Fiber dosage, residual strength, fiber reinforced concrete (FRC), flexural performance, macro fibers, polypropylene, polyolefin

Abstract

Synthetic macro fibers can be viable alternatives for partial or full replacement of conventional steel mesh in concrete elements with continuous support such as slabs-on-ground or shotcrete. Macro synthetic fibers are used in concrete reinforcement due to their durability, ease of use, cost effectiveness, environmentally friendly and carbon footprint compared to traditional steel reinforcement. Fiber dosage can be engineered to provide a desired level of crack resistance control, post crack tensile and flexural-moment capacity, or both. Similar to steel mesh for which the size and spacing are calculated to provide the required reinforcement ratio, the dosage of fibers is also calculated to satisfy engineering requirements.
Synthetic fiber reinforcement is classified conformity with the standard pr EN 14889-2 (Fibers - for use in concrete - Part 2: Polymer fibers - Definitions, specifications, and conformity) their equivalent diameter and type.

Group Ia: Micro Fibers: ≤ 0,05 mm in (equivalent) diameter; mono-filamented;
Group Ib: Fibrillated Fibers: fibrillated;
Group Ic: Meso Fibers: 0,05 mm < (equivalent) diameter ≤ 0,30 mm; mono-filamented;
Group II: Macro Fibers: > 0,30 mm in (equivalent) diameter; mono-filamented.

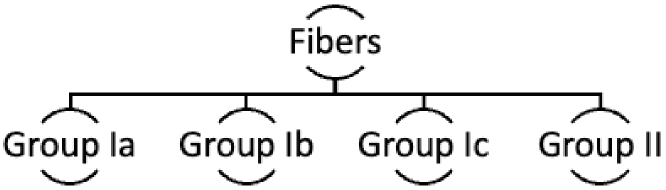

Figure 1: Fibers for concrete

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Design of Concrete Slabs on Ground: Yield Line Theory

Yield line analysis accounts for the redistribution of moments and formation of plastic hinges in the slab. These plastic hinge regions develop at points of maximum moment and cause a shift in the elastic moment diagram. Using plastic hinges permits the use of the full moment strength of the slab and an accurate determination of its ultimate load strength. (ACI 360R-10). Plastic hinge formation depends on the residual strength of the plate and these residual values are determined by using the values called fr_1 and fr_4 (residual strength) in the section analysis of EN 14651 standard. (ACI 544.4R-18, TR 34-4th). Shrinkage and crack width are calculated according to EN 1992-1-1(2004-2023).

EXPERIMENTAL STUDY

Sieve analysis of aggregates used in the concrete design created in the experimental study was selected in accordance with TS 13515. Mix design for C30/37 concrete class is given below in Table 1.

Table 1. Concrete Mix Design

Sample	1m3 Concrete, kg/m^3
Water	176
Cement	320 (CEM II42.5N)
Coarse aggregate	940
Fine aggregate	916
Super plasticizer	3.2 (%1) (Rheocon S37)
Fibers	2 (Fibtwist® FT 54)

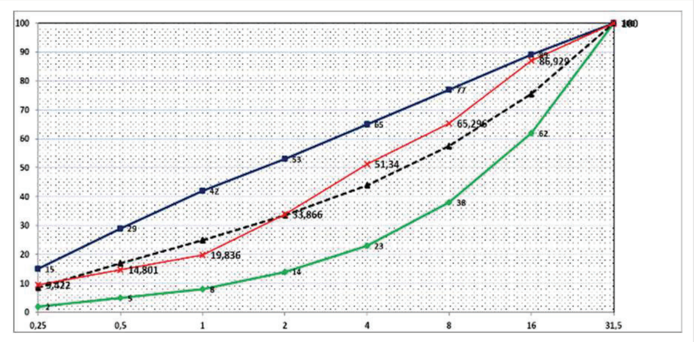


Figure 2: Aggregate Sieve Analysis – (TS 13515)

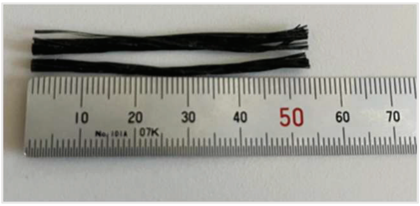


Figure 3: Macro Synthetic Fiber Reinforcement - Fibtwist® FT 54

Bending tests were carried out according to EN 14651 standard on the concrete samples produced by the above-mentioned concrete mix. In the test carried out the prisms were turned sideways and the concrete surfaces touching the molds were seated freely on two steel supporting rollers. The span length is 500 mm. Center point load ½ of the span length was applied. The load was applied closed-loop testing machine and crack width at the mid-span was measured by using cmod (crack mouth opening displacement) transducers. All tests were performed at the age of 28 days and six samples were used in test. (15*15*60 cm). The loading rate was 0,05 mm/min up to cmod 0,1 mm, and 0,2 mm/min for the cmod between 0,1 mm- 4 mm. From the load cod diagrams obtained, results are summarized as seen in figure 4.

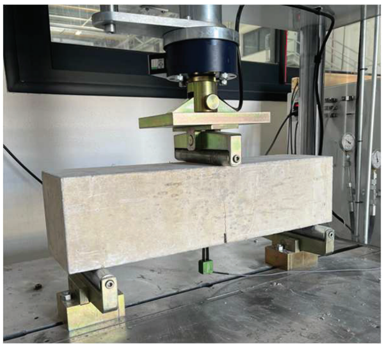


Figure 4: EN 14651 Test Machine

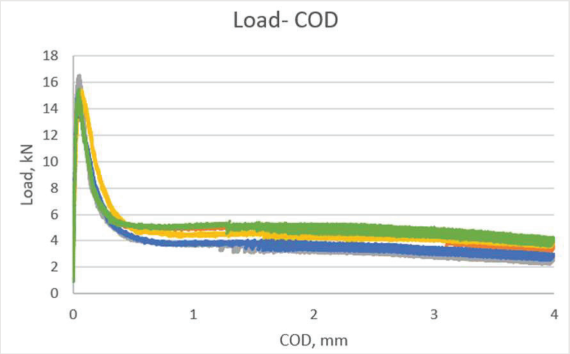


Figure 5: Load - COD curve

Slab on Ground Concrete Design with Macro Synthetic Fiber

Slab thickness	200 mm,h
Modulus of subgrade reaction	0.05 N/mm^3, k
Concrete class	C30/37
Wheel Load	60 kN
Wheel Contact Area	500,250 mm,mm
Pressure of wheel	0.8 MPa
Residual Strengths	fr1= 1.3 MPa fr4=1.1 MPa

Table 2: Project Details

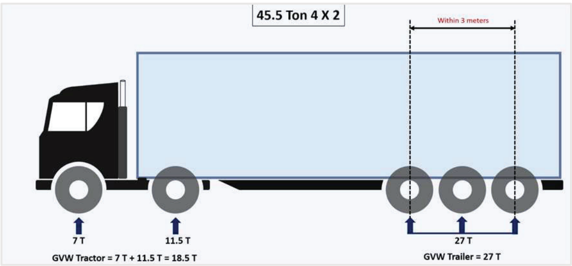


Figure 6: Max axle 11.5 tons (≈6t per wheel) – Truck Load

Project Data;

Reinforcement type; Macro-synthetic fiber

2 kg/m³ Fibtwist® FT 54

Concrete class; C30/37

Slab thickness; h = 200 mm

Residual strength at CMOD 0.5; $f_{R,1}$=1.3 N/mm^2

Residual strength at CMOD 3.5; $f_{R,4}$=1.1 N/mm^2

Mean axial tensile strength relating to CMOD 0.5; $\sigma r1 = 0.45 * f_{R,1} = 0.585$ N/mm^2

Mean axial tensile strength relating to CMOD 3.5;

$\sigma r4 = 0.37 * f_{R,4} = 0.407$ N/mm^2

Effective depth of reinforcement;

d = 0.75*h= 150 mm

Partial safety factors

Concrete (with or without fiber); $\gamma c = 1.50$

Reinforcement (bar or fabric); $\gamma s = 1.15$

Permanent; $\gamma G = 1.20$

Variable; $\gamma Q = 1.50$

Dynamic loads; $\gamma D = 1.60$

Subgrade reaction

Modulus of subgrade reaction; k = 0.05 N/mm^3

Concrete details

Characteristic compressive cylinder strength;

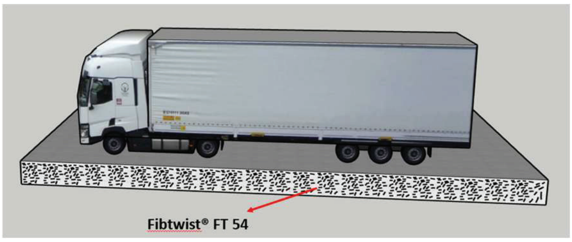
fck = 30 N/mm^2

Characteristic compressive cube strength;

fcu = 37 N/mm^2

Mean value of compressive cylinder strength;

fcm = fck + 8 N/mm^2 = 38 N/mm^2



Mean value of axial tensile strength;

fctm = 0.3 N/mm^2 * (fck/ 1 N/mm^2)$^{2/3}$ = 2.9 N/mm^2

Flexural tensile strength;

fctd,fl = fctm * (1.6 - h / 1m) / γc = 2.7 N/mm^2

Design concrete compressive strength (cylinder);

fcd = fck / γc = 20.0 N/mm^2

Secant modulus of elasticity of concrete;

Ecm = 22 kN/mm^2

[fcm/ 10 N/mm^2]$^{0.3}$ = 33 kN/mm^2

Poisons ratio; n = 0.2

Radius of relative stiffness (Eqn. 20);

$l = [Ecm * h^3 / (12 * (1 - n^2) * k)]^{0.25} = 822$ mm

Characteristic of system (Eqn. 33);

$l = (3 * k / (Ecm * h^3))0.25 = 0.869$ m^{-1}

Moment capacity

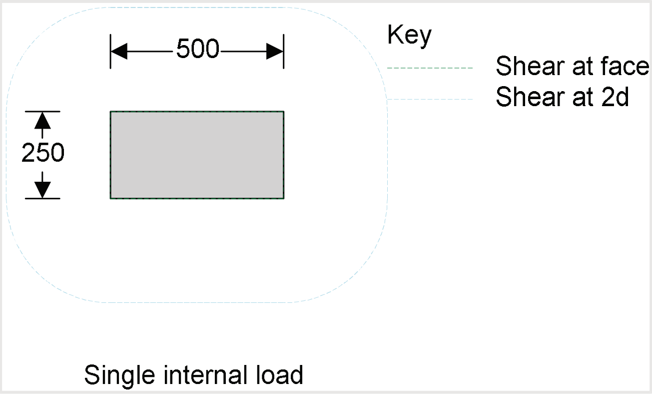
Negative moment capacity (Eqn. 2);

$Mn = Mun = f_{ctd,fl} * (h^2 / 6) = 18.0$ kNm/m

Positive moment capacity (Eqn. 6);

$Mp = Mu = h^2 / \gamma c * (0.29 * \sigma r4 + 0.16 * \sigma r1) = 5.6$ kNm/m

Load 1 - Single internal 500 x 250 point load



Loading length; ll = 500mm

Loading width; lw = 250mm

Permanent load; Gk = 0.0 kN

Variable load; Qk = 0.0 kN

Dynamic load; Dk = 60.0 kN

Contact radius ratio

Equivalent contact radius ratio;

a = $[(ll \, {}^*lw) / p]^{0.5}$ = 199.5 mm

Radius ratio; a / l = 0.243

Ultimate capacity under single internal concentrated loads

For a/l equal to 0 (Eqn. 21);

Pu_0 = 2*p* (Mp + Mn) = 148.7 kN

For a/l equal to 0.2 (Eqn. 22);

Pu_0.2 = 4*p* (Mp + Mn) / [1 - (a / (3* l))] = 323.6 kN

Thus for a / l equal to 0.243;

Pu = min (Pu_0.2, Pu_0 + (Pu_0.2 - Pu_0)*(a / (l* 0.2))) = 323.6 kN

Check ultimate load capacity of slab

Number of loads; N = 1

Loading applied to slab; Fuls = N* ((Gk* γG) + (Qk*γQ) + (Dk* γD)) = 96.0 kN

Utilisation;

Fuls / Pu = 0.297

PASS - Total slab capacity exceeds applied load

Punching shear at the face of the loaded area

Shear factor;

$k^2 = 0.6^* (1 - fck / 250N/mm^2) = 0.53$

Length of perimeter at face of loaded area;

$u_0 = 2^* (ll + lw)$ = 1500 mm

Shear stress at face of contact area;

$v_{max} = 0.5^*k^{2*} fcd = 5.280 \ N/mm^2$

Maximum load capacity in punching;

Pp,max = vmax*u_0*d = 1188.0 kN

Utilisation;

Fuls / Pp,max = 0.081

PASS - Total slab capacity in punching at face of loaded area exceeds applied load

Punching shear at the critical perimeter

Shear factor;

ks = min(1 + $(200mm / d)^{0.5}$, 2) = 2.00

Minimum shear stress at 2d from face of load;

$v_{Rd,c,min} = 0.035^* ks^{3/2*} (fck / 1N/mm^2)^{0.5*} \ 1N/mm^2 = 0.542 \ N/mm^2$

Length of perimeter at 2d from face of load;

$u_1 = 2^* (ll + lw + 2^* p^*d)$ = 3385 mm

Max. load capacity in punching at 2d from face;

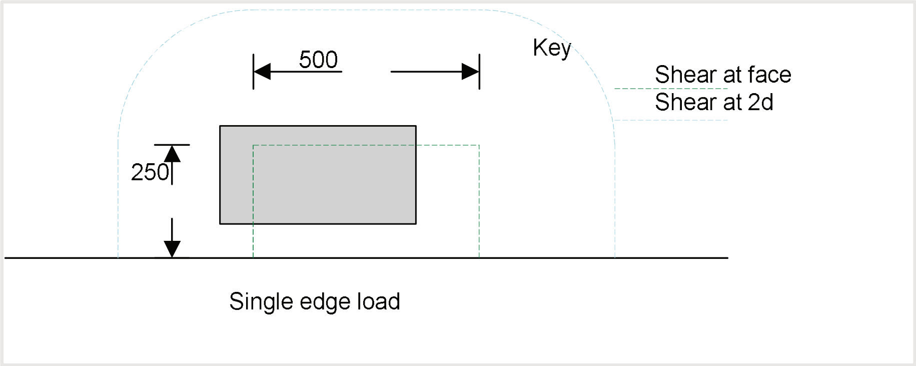
$Pp = v_{Rd,c,min}{}^* \ u_1{}^*d$ = 275.3 kN

Utilisation;

$F_{uls} / Pp = 0.349$

PASS - Total slab capacity in punching at 2d from face of loaded area exceeds applied load

Load 2 - Single edge 500 x 250 point load



Loading length; ll = 500mm

Loading width; lw = 250mm

Edge distance y; ey = 0mm

Permanent load; Gk = 0.0 kN

Variable load; Qk = 0.0 kN

Dynamic load; Dk = 60.0 kN

Contact radius ratio

Equivalent contact radius ratio;

a = $[(ll^* lw) / p]^{0.5}$ = 199.5 mm

Radius ratio;

a / l = 0.243

Ultimate capacity under single edge concentrated loads

For a/l equal to 0 (Eqn. 23);

Pu_0 = [p*(Mp + Mn) / 2] + 2* Mn = 73.2 kN

For a/l equal to 0.2 (Eqn. 24);

Pu_0.2 = [p*(Mp + Mn) + 4* Mn] / [1 - (2*a / (3* l))] = 174.7 kN

Thus for a / l equal to 0.243;

Pu = min(Pu_0.2, Pu_0 + (Pu_0.2 - Pu_0)* (a / (l* 0.2))) = 174.7 kN

Percentage of aggregate transfer;

Pagg = 15 %

Total effective edge capacity (cl.7.9.1);

Pu,total = min(Pu / (1 - Pagg), Pu / (1 - 0.5), 4* p* (Mp + Mn) / [1 - (a / (3 * l))]) = 205.5 kN

Check ultimate load capacity of slab

Number of loads; N = 1

Loading applied to slab;

Fuls = N*((Gk* γG) + (Qk*γQ) + (Dk* γD)) = 96.0 kN

Utilisation;

Fuls / Pu_total = 0.467

PASS - Total slab capacity exceeds applied load

Punching shear at the face of the loaded area

Shear factor;

k_2 = 0.6* (1 - fck / 250N/mm^2) = 0.53

Length of perimeter at face of loaded area;

u_0 = 2* (lw + ey) + ll = 1000 mm

Shear stress at face of contact area;

vmax = 0.5*k_2* fcd = 5.280 N/mm^2

Maximum load capacity in punching;

Pp,max = v_{max}* u_0* d = 792.0 kN

Utilisation;

Fuls / Pp,max = 0.121

PASS - Total slab capacity in punching at face of loaded area exceeds applied load

Punching shear at the critical perimeter

Shear factor;

ks = min(1 + (200mm / d)$^{0.5}$, 2) = 2.00

Minimum shear stress at 2d from face of load;

vRd,c,min = 0.035* ks$^{3/2}$* (fck / 1N/mm^2)$^{0.5}$* 1N/mm^2 = 0.542 N/mm^2

Length of perimeter at 2d from face of load;

u_1 = ll + 2* (lw + ey + p* d) = 1942 mm

Max. load capacity in punching at 2d from face;

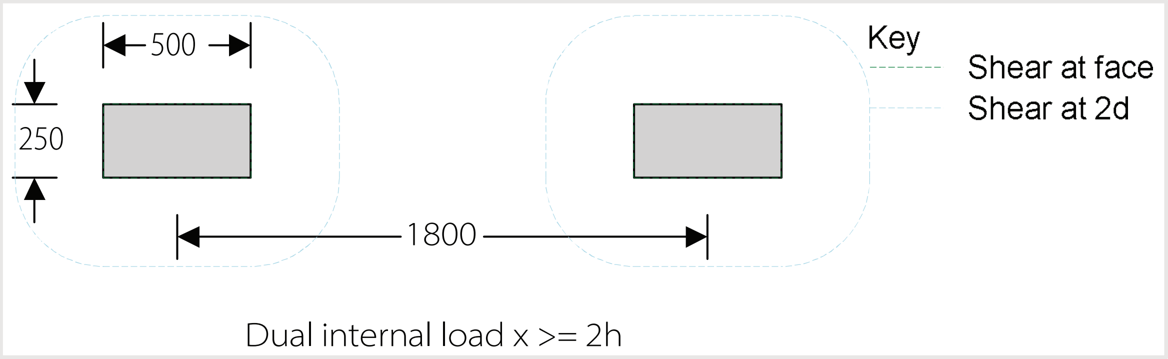
Pp = vRd,c,min*u_1* d = 158.0 kN

Utilisation;

Fuls / Pp = 0.608

PASS - Total slab capacity in punching at 2d from face of loaded area exceeds applied load

Load 3 - Dual internal 500 x 250 point load



Loading length; ll = 500mm

Loading width; lw = 250mm

Distance x; x = 1800mm

Permanent load; Gk = 0.0 kN

Variable load; Qk = 0.0 kN

Dynamic load; Dk = 60.0 kN

Contact radius ratio

Equivalent contact radius ratio; a = $[(ll^* lw) / p]^{0.5}$ = 199.5 mm

Radius ratio; a / l = 0.243

Ultimate capacity under dual internal concentrated loads

For a/l equal to 0 (Eqn. 27);

Pu_0 = [2 * p + (1.8* x / l)] * [Mp + Mn] = 242 kN

For a/l equal to 0.2 (Eqn. 28);

Pu_0.2 = [4*p / (1 - (a / (3 *l))) + 1.8 *x / (l - (a / 2))]* [Mp + Mn] = 429.8 kN

Thus for a / l equal to 0.243;

Pu = min(Pu_0.2, Pu_0 + (Pu_0.2 - Pu_0)* (a / (l*0.2))) = 429.8 kN

Check ultimate load capacity of slab

Number of loads;N = 2

Loading applied to slab;

Fuls = N* ((Gk*γG) + (Qk* γQ) + (Dk*γD)) = 192.0 kN

Utilisation;

Fuls / Pu = 0.447

PASS - Total slab capacity exceeds applied load

Punching shear at the face of the loaded area

Shear factor;

k_2 = 0.6* (1 - fck / 250N/mm^2) = 0.53

Length of perimeter at face of loaded area;

u_0 = 4* (ll + lw) = 3000 mm

Shear stress at face of contact area;

v_{max} = 0.5*k_2*fcd = 5.280 N/mm^2

Maximum load capacity in punching;

Pp,max = vmax* u_0* d = 2376.0 kN

Utilisation;

Fuls / Pp,max = 0.081

PASS - Total slab capacity in punching at face of loaded area exceeds applied load

Punching shear at the critical perimeter

Shear factor;

ks = min(1 + (200mm / d)$^{0.5}$, 2) = 2.00

Minimum shear stress at 2d from face of load;

vRd,c,min = 0.035* ks$^{3/2}$* (fck / 1N/mm^2)$^{0.5}$* 1N/mm^2 = 0.542 N/mm^2

Length of perimeter at 2d from face of load;

u_1 = 4*(lw + 2* p* d + ll) = 6770 mm

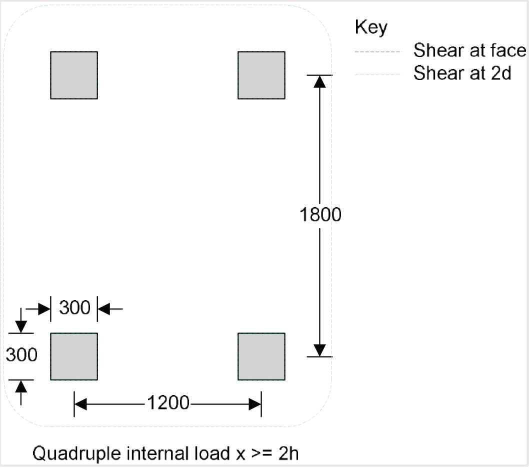
Max. load capacity in punching at 2d from face;

Pp = vRd,c,min*u_1* d = 550.6 kN

Utilisation;Fuls / Pp = 0.349

PASS - Total slab capacity in punching at 2d from face of loaded area exceeds applied load

Load 4 - Quadruple internal 300 x 300 point load



Quadruple internal load x >= 2h

Loading length; ll = 300mm
Loading width; lw = 300mm
Distance x; x = 1200mm
Distance y; y = 1800mm
Permanent load; Gk = 0.0 kN
Variable load; Qk = 0.0 kN
Dynamic load; Dk = 45.0 kN

Contact radius ratio

Equivalent contact radius ratio;
a = [(ll* lw) / p]$^{0.5}$ = 169.3 mm
Radius ratio; a / l = 0.206

Ultimate capacity under single internal concentrated loads

For a/l equal to 0 (Eqn. 21);
Pu_0 = 2*p* (Mp + Mn) = 148.7 kN
For a/l equal to 0.2 (Eqn. 22);
Pu_0.2 = 4*p* (Mp + Mn) / [1 - (a / (3*l))] = 319.3 kN
Thus for a / l equal to 0.206;
Pu = min(Pu_0.2, Pu_0 + (Pu_0.2 - Pu_0) * (a / (l*0.2))) = 319.3 kN
4 No. individual;
Pu_4x1 = 4 *Pu = 1277.3 kN

Ultimate capacity under dual internal concentrated loads

For a/l equal to 0 (Eqn. 27);
Pu_0 = [2*p + (1.8* min(x, y) / l)]* [Mp + Mn] = 210.9 kN
For a/l equal to 0.2 (Eqn. 28);
Pu_0.2 = [4*p / (1 - (a / (3* l))) + 1.8*min(x, y) / (l - (a / 2))]* [Mp + Mn] = 388.7 kN
Thus for a / l equal to 0.206;
Pu = min(Pu_0.2, Pu_0 + (Pu_0.2 - Pu_0)* (a / (l *0.2))) = 388.7 kN
2 No. dual;
Pu_2x2 = 2*Pu = 777.3 kN

Ultimate capacity under quadruple internal concentrated loads

For a/l equal to 0 (Eqn. 29);
Pu_0 = [2 *p + 1.8 *(x + y) / l] *[Mp + Mn] = 304.2 kN
For a/l equal to 0.2 (Eqn. 30);
Pu_0.2 = [4 *p / (1 - (a / (3 *l))) + 1.8 *(x + y) / (l - (a / 2))] * [Mp + Mn] = 492.7 kN
Thus for a / l equal to 0.206;
Pu = min(Pu_0.2, Pu_0 + (Pu_0.2 - Pu_0)* (a / (l *0.2))) = 492.7 kN
Quadruple;
Pu_1x4 = Pu = 492.7 kN
Ultimate load capacity for 4 No. loads;
Pu = min(Pu_4x1, Pu_2x2, Pu_1x4) = 492.7 kN

Check ultimate load capacity of slab

Number of loads;
N = 4
Loading applied to slab; Fuls = N*((Gk* γG) + (Qk*γQ) + (Dk* γD)) = 288.0 kN
Utilisation;
Fuls / Pu = 0.585
PASS - Total slab capacity exceeds applied load
Punching shear at the face of the loaded area
Shear factor;
k_2 = 0.6* (1 - fck / 250N/mm^2) = 0.53
Length of perimeter at face of loaded area;
u_0 = 8* (ll + lw) = 4800 mm
Shear stress at face of contact area;
v_{max} = 0.5* k^2* fcd = 5.280 N/mm^2
Maximum load capacity in punching;
Pp,max = vmax*u_0*d = 3801.6 kN
Utilisation;
Fuls / Pp,max = 0.076
PASS - Total slab capacity in punching at face of loaded area exceeds applied load
Punching shear at the critical perimeter
Shear factor;
ks = min(1 + (200mm / d)$^{0.5}$, 2) = 2.00
Minimum shear stress at 2d from face of load;
vRd,c,min = 0.035* ks$^{3/2}$* (fck / 1N/mm^2)$^{0.5}$*1N/mm^2 = 0.542 N/mm^2
Length of perimeter at 2d from face of load;
u_1 = 2*(lw + y + ll + x + 2* p*d) = 9085 mm
Max. load capacity in punching at 2d from face;
Pp = VRd,c,min*u_1*d = 738.9 kN
Utilisation; Fuls / Pp = 0.390
PASS - Total slab capacity in punching at 2d from face of loaded area exceeds applied load

All equations are explained in TR 34-4th edition.

Shrinkage Calculation

Selected cement category: Class N

Drying shrinkage coefficients:

α_{ds1}= 4

α_{ds2}= 0,12

Relative humidity :70%

Humidity Factor:

$\beta_{RH}=1.55[1\text{-}RH/(100\%)]^{\wedge 3}= 1.018$

Basis drying shrinkage:

$\varepsilon_{cd,0}=0{,}85\beta RH/10^{\wedge 6}\ [(220+110\alpha_{ds}1)\exp\varepsilon$ $(-(\alpha_{ds2}*fcm)/10MPa)]$ $=0.362‰$

Notional size = ho =400 mm

Size coefficient = kh = 0.725

Age factor:

$Bds(t) =(t\text{-}t_s)/(t\text{-}t_s + 0.04\sqrt{(\ 〖ho〗\ ^{\wedge 3}\ )})$

Age of concrete (time from casting to present day),t = 50 years

Age of concrete when drying shrinkage starts,ts = 7 days

$\varepsilon cd(t)= \beta ds(t)*k_h*\ \varepsilon_{cd,0}$

Autogenous shrinkage:

$\varepsilon ca(\infty) = 2.5\ (f_{ck}\text{-}10MPa)*10\text{-}^{6}$

Autogenous development factor:

$\beta as(t) = 1\text{-}\exp(\text{-}0.2t^{0.5})$

$\varepsilon ca(t) = \beta as(t)*\ \varepsilon ca\ (\infty)$

Total shrinkage at t = 50 years

$\varepsilon cs = \varepsilon cd + \varepsilon ca = 0.308‰$

Crack width calculation

Restraint factor = Rax = 0.5

Time coefficient kt =0.4

Crack producing strain:

$\varepsilon sm\text{-}\ \varepsilon cm =Rax*\varepsilon cs\ \text{-}kt*\ fctm/Ecm$

Crack spacing by geometry = Smax =1/2 max(l-w)= 3000 mm

Max crack width: wk = Smax* $(\varepsilon sm\text{-}\ \varepsilon cm)$ =0.36 mm✓

Design crack width = 0.4 mm

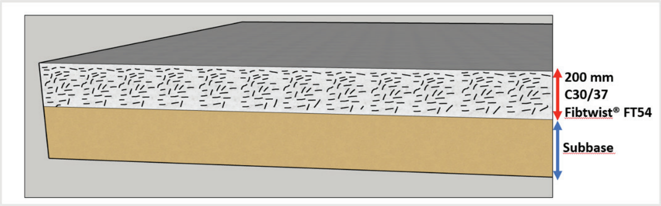


Figure 8: Cross section

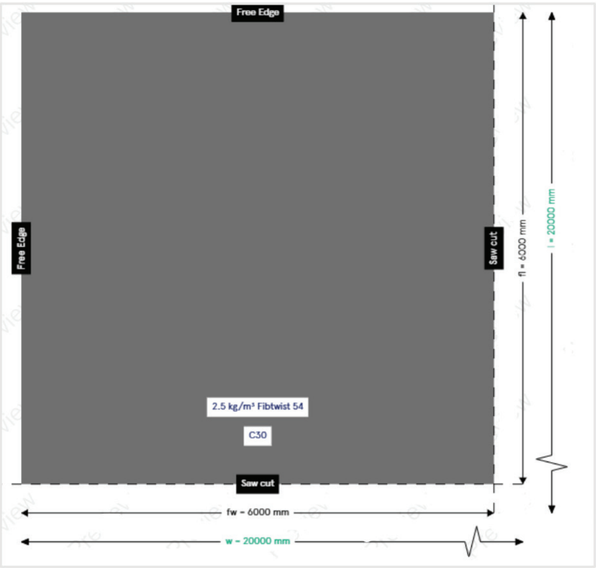
Plan view

Slab length: 20 m

Slab width: 20 m

Saw cut joint spacing: 6*6 m,m

Saw cut depth:30%*Slab thickness = 60 mm



Result

Solution with Macro Fiber	
Dosage, kg/m³	2
Fiber type	Fibtwist® FT 54
Slab Thickness, mm	200
Concrete class	C30/37
Truck Load	≈ 45t

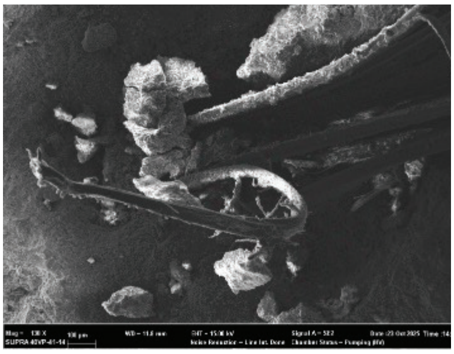
Microstructural Analysis of Fiber–Cement Interfacial Bonding (SEM Observations)

The SEM micrographs obtained at magnifications of 50×, 56×, and 130× provide valuable insights into the interfacial characteristics between the synthetic fibers and the cementitious matrix. At lower magnification (50×), the overall dispersion and embedment of fibers within the hardened matrix are evident, demonstrating uniform distribution and adequate bonding. The matrix appears well consolidated around the fibers, with no significant interfacial voids, indicating effective mechanical interlocking and proper mixing during casting.

At 56× magnification, the interfacial transition zone (ITZ) between the fiber and the surrounding matrix can be clearly observed. The hydration products, particularly calcium silicate hydrate (C–S–H) phases, are seen to adhere closely to the fiber surface, confirming the establishment of a continuous and compact interfacial layer. This dense microstructure enhances stress transfer efficiency from the matrix to the fiber, which is critical for crack-bridging performance.

At higher magnification (130×), a more detailed morphology of the ITZ is revealed. The fiber surface exhibits a roughened texture, which promotes better mechanical anchorage of hydration products. The dense packing of C–S–H and other hydration compounds around the fiber further reinforces the fiber–matrix adhesion. Such intimate contact between the two phases suggests a synergistic interaction involving both mechanical interlocking and physicochemical adhesion.

Overall, the SEM analysis confirms that the Fibtwist® FT 54 synthetic fibers develop a strong interfacial bond with the cement matrix. This bond is primarily governed by the combined effects of surface roughness, microstructural densification, and the adhesion of hydration products. Consequently, the presence of these Fibtwist® FT 54 fibers significantly enhances the composite's resistance to crack propagation and contributes to improved ductility and toughness of the cementitious system.



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