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Performance of concrete structures with a combination of normal SCC and fiber SCC

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Abstract. Fiber reinforced concretes exhibit higher tensile strength depending on the percent and type of the fiber used. These concretes are used to reduce cracks and improve concrete behavior. The use of these fibers increases the production costs and reduces the compressive strength to a certain extent. Therefore, the use of fiber reinforced concrete in regions where higher tensile strength is required can cut costs and improve the overall structural strength. The behavior of fiber reinforced concrete and normal concrete adjacent to each other was investigated in the present study. The concrete used was self-compacting and did not require vibration. The samples had 0, 1, 2 and 4 wt% polypropylene fibers. 15 cm sample cubes were subjected to uniaxial loads to investigate their compressive strength. Fiber Self-Compacting Concrete was poured in the mold up to 0, 30, 50, 70 and 100 percent of the mold height, and then Self-Compacting Concrete without fiber was added to the empty section of that mold. In order to investigate concrete behavior under bending moment, concrete beam samples with similar conditions were prepared and subjected to the three-point bending flexural test. The results revealed that normal Self-Compacting Concrete and Fiber Self-Compacting Concrete may be used in adjacent to each other in structures and structural members. Moreover, no separation was observed at the interface of Fiber Self-Compacting Concrete and Self-Compacting Concrete, either in the cubic samples under compression or in the concrete beams under bending moment.

Keywords: fiber self-compacting concrete; compressive strength; moment-curvature diagram; polypropylene fiber

1. Introduction

Numerous studies have been conducted on concretes, special concretes and fiber reinforced concretes with different compound percentages (Ge *et al.* 2015). Addition of different fibers to concrete is a way of enhancing its tensile strength. The fiber type as well as the percentage of the mixed fibers affects the tensile strength, compressive strength, Young's modulus and concrete slump. Mertol *et al.* investigated heavyweight and lightweight steel-fiber-reinforced concrete beams. Sample sizes of the reinforced concrete beams were 3500×250×180 mm, and 20 models were used to examine the concrete behavior. They studied heavyweight and lightweight concretes. The results of compressive strength in heavy and normal reinforced concretes revealed that increased steel fibers in normal reinforced beams may decrease/increase the beam strength, but increase flexural strength of the beam at heavy reinforced cross-sections.

Yoo *et al.* (2015) studied the behavior of steel-fiber-reinforced concrete beams. The behavior of concrete beams subjected to quasi-static and impact loadings were investigated in the present study. The compressive strengths of the prepared concrete samples were 180, 90 and 49 MPa. Our experiments showed that the deformations of the beam samples subject to loadings were dependent on the percentage of the fibers used as well as the compressive strength of the fiber-free sample. The dependency is caused by the bending and shear cracks created along the concrete beam, the development of which at the central region is prevented by the steel fibers once the micro cracks are created.

Yap *et al.* (2015) conducted studies on the effect of different steel ratios in normal and lightweight concretes in 2015. Crushed stone aggregates and almond shells were used in their study to prepare the concrete samples. The ratios of steel fibers used in the reinforced concretes were 55, 65 and 80 percent. They also conducted studies on the behavior of concrete beams made up of steel fibers and almond shells. The amounts of steel fibers used in these studies were 0.25, 0.5, 0.75 and 1 percent. Generally, studies indicate that addition of steel fibers increases mechanical properties and tensile strength of concretes. Moreover, the results suggested that as steel fibers increase, the torsional strength during primary, secondary and failure cracks enhances. In 2016, Siddique *et al.* studied mechanical properties of self-compacting concretes (SCC) containing steel fibers and fly ashes. The amounts of steel fibers used in their study were 0.5, 1 and 1.5 percent.

Another study was conducted by Grabois *et al.* in 2016 on the behavior of self-compacting concretes containing steel fibers and fly ashes. The properties of fresh and hardened concrete were studied in their experiments. Investigation of the hardened concrete properties showed that no significant difference was observed in the fly-ash-

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free concrete's Young's modulus when 10 percent steel fibers were added to the cement. The results from the two studies indicate that addition of steel fibers affect the self-compacting concrete slump at varying degrees. The reason may be due to the various steel fiber lengths used in the experiments. Prasad *et al.* (2016) applied a periodic loading to a self-compacting reinforced concrete beam containing natural fibers to study the beam behavior. Adding fiber increases the energy absorption capacity of the concrete, and this adds to the importance of studying the concrete behavior under periodic loading. The results of the laboratory tests conducted on the fiber-reinforced self-compacting concrete in this study were presented in the form of hysteresis curves, stress-strain and moment-curvature diagrams, as well as the concrete (beam) stiffness and the energy absorbed by the same. Tuan *et al*. (2014) conducted a comparative study on self-compacting concrete specimens containing propylene, steel, and hybrid fibers. Upon testing the wet and dry concrete specimens containing different fiber percentages, their respective behaviors were duly studied. Adding fiber increased the tensile and flexural strengths of the specimens, but reduced their compressive strengths. The polypropylene fibers had a lesser effect on the tensile and flexural strengths of the concrete as compared with the steel fibers. In addition, the reductions in compressive strength caused by the polypropylene and hybrid fibers were less than that caused by the steel fibers, whereas the increases in toughness caused by the former were greater than that caused by the latter. Li and Deny (2007) studied the mechanical behavior (flexural impact strength, toughness, and failure modes) of concrete specimens containing steel and hybrid fibers. Their results showed that increasing the total fiber volume percentage to 1.5% considerably increased the concrete toughness. In addition, mixing the two fibers (hybrid fiber) produced better results in terms of flexural strength and failure modes. Kandasamy and Akhila (2015) studied and modeled the behavior of the steel fiber self-compacting concrete (SF-SCC). They prepared 30 mixed specimens of wet and dry self-compacting concrete containing different percentages of fiber, cinder/fly ash, and plasticizer, and compared the results obtained from the loading tests conducted on these specimens at the age of 28 days. Ultimately, they presented an optimum concrete mix model upon due consideration of the relevant variables. Thomee *et al.* (2006) proposed a model for steel-fiber-reinforced concretes which showed the nonlinear behavior of the particles used in these concretes. This model was classified as a finite element model, whereas the other models used the standard materials parameters. The parameters used in the proposed model were obtained from actual laboratory tests and this model was found to be in good agreement with the other models proposed for simulating the behavior of fiber-reinforced concretes.

The effect of fiber length on the behavior of concretes has been investigated in numerous studies. The effect of the applied fiber type in the concrete is also significant. Lanzoni *et al*. (2012) presented the results of their study on polypropylene- and steel-fiber-reinforced concretes in 2012. Bending behavior, toughness, and shrinkage cracks in the samples were studied. The fibers used in their study included 5 types with lengths of 40, 35, 40, 50 and 70 mm. 4 types were made of polymers and the other of steel. The results showed that crack tip opening displacement (CTOD) was related to the applied fiber types. Yin *et al.* studied the effect of compound fibers on the triaxial compressive strength in concretes. The applied fiber was a combination of steel and polypropylene fibers. A comparison between the Mohr failure envelopes of steel- and polypropylene-fiber-reinforced concretes indicates that the effect of fiber increase on the failure mode is similar in both cases. Jameran *et al.* (2015) studied the behavior of steel- and polypropylene-fiber-reinforced concretes subjected to high temperatures. The experiments suggested that fiber-reinforced concretes exhibited higher strength and more durability than normal concretes. Polypropylene-fiber-reinforced concretes were more affected by heat than steel-fiber-reinforced concretes. Bosnjak *et al.* (2013) conducted studies on high-strength concretes containing polypropylene fibers subjected to heat. Their studies were conducted on the behavior of high-strength concretes in temperatures ranging from room temperature up to 300 °C. The results showed that temperature increase increased the permeability of polypropylene-free concrete. In case of samples containing propylene fibers, the permeability varies to a slight degree in that temperature increases of up to 200°C do not affect the permeability of polypropylene reinforced concretes.

Numerous researches have studied the behavior of concretes containing polypropylene (Yap). Mazaheripour *et al.* investigated the effect of polypropylene fibers on the properties of fresh and hardened self-compacting, lightweight-aggregate concrete in 2011. The weight of self-compacting, lightweight concretes were 75 percent of that of normal SCCs, and a 40 percent decrease in the SCC slump was observed by the addition of polypropylene fibers. The results suggested that addition of polypropylene fibers increased the flow time of SCC in the V-funnel test, the maximum of which occurred at 0.15% polypropylene fibers. The maximum tensile and compressive strength for polypropylene-fiber-reinforced SCC was seen at fiber amounts of higher than 20%, which were 14% of the normal concrete.

Energy absorption capacity of polypropylene-fiber-reinforced concrete was studied by Grdic *et al.* (2015), in which two types of polypropylene fibers were used. Water-cement ratio varied between 0.5 and 0.7. The two types of polypropylene differed in tensile strengths. Nobili *et al.* (2013) conducted experimental studies on polypropylene-reinforced concrete cobblestones. The results suggested that use of polypropylene enhanced the attachment of block under moving loads. Noushini *et al*. (2013) investigated the effect of polyvinyl alcohol (PVA) on the properties and dynamic behavior of reinforced concretes. The lengths of PVA fibers used in their study were 20 and 12 mm. Moreover, fly ash together with Portland cement was used in the combination. Dynamic characteristics of the concrete samples at the age of 14 and 28 days indicated that the damping ratio decreased with increasing age. Moreover, the results also suggested that after a specific amount, addition of PVA fibers had slight effects on increasing the damping ratio and ultimate tensile strength.

Cao *et al.* (2014) used the digital image method to study the failure/fracture behavior of a polypropylene-reinforced concrete beam. They found that the fiber additive improved the flexural strength of the beam; and used the obtained images to examine the three-point bending failure in the beam. Their results showed that adding fibers increased fracture toughness. Theoretically, fracture energy can be increased 47 times by adding 3.2% of fiber to the concrete. To strike a balance between increased compressive strength and increased toughness, a fiber percentage of 1.6 must be applied. Gouveia *et al.* (2011) studied the cracking behavior in the fiber-reinforced concrete used in shell structures, using the finite element method and the shell theory for modeling thin fiber-reinforced concrete sheets. They used the actual results obtained for concrete from the stress-strain and the moment-curvature diagrams to model the relevant structural behaviors. To simulate spatial/non-planar nonlinear buckling and shearing, they divided the concrete shells into different layers (used as elements/members).

Ramezanipour *et al.* (2013) investigated stability, durability, physical conditions and mechanical properties of concrete pads containing polypropylene fibers. The amount of fibers used in the concrete mixtures ranged from 0 to 4 kg/m^3. The minimum depth of permeability was 7.5 mm, which was achieved at 0.7 kg/m^3 amount of polypropylene. However, increasing amounts of fiber could result in increased water permeation. Al-qadi and Al-zaidyeel studied the behavior of propylene-fiber-reinforced SCCs subjected to heat. The experimented temperatures ranged from 20°C to 600°C. The water-cement ratio in the samples was 0.32 and the polypropylene ratios were 0.15, 0.1, 0.05 and 0. The results revealed that addition of polypropylene reduced the flow slump in the V-funnel test. The use of recycled aggregates is of significant value from the cost and environmental perspectives (Jeon). Akca *et al.* (2015) studied the behavior of polypropylene-fiber-reinforced concretes containing recycled aggregates. Different percentages of recycled aggregates as well as propylene fibers were considered. The amounts of compound fibers used in the sample preparation process were 0, 1 and 1.5 percent. The mixture of recycled aggregates in these concrete samples included brick fragments, recycled concrete, gravel and gypsum.

The addition of extra materials, especially different fibers, to concrete increases building costs and reduces public applications. A solution to this problem is goal-directed consumption of concrete in proper locations as well as proper use of additives. In fact, fiber reinforced concretes may be used in combination with normal concretes at appropriate locations to reduce costs. Considering their unique properties, fiber reinforced concretes may be used in exterior sections to increase abrasion resistance, and in interior sections and around core connections to increase flexural strength. In order to investigate the behavior of fiber reinforced concretes, the behavior of normal concrete blocks adjacent to fiber reinforced concrete blocks is studied.

2. Experimental study

The behavior of fiber and normal concretes as well as concrete blocks made of both concretes was investigated in the present study. In order to prepare the concrete block, a combination of fresh fiber reinforced concrete and fresh normal concrete was poured in a mold to dry. No vibrations or movements were applied to the molds to achieve the minimum mixture of the two concrete types. Moreover, to eliminate the need for vibration, plasticizers were used. Compressive and bending tests were performed on the prepared blocks at the ages of 7 and 28 days.

Table 1 Fiber qualifications

Name	Diameter (mm)	Length (mm)	Density (gr/cm^3)	Tensile strength (MPa)
PP	0.045	12	1100	550

Table 2 Properties of the concrete mix

Name	Cement Weight Ratio (375 kg/m^3)			Aggregate Ratio		Slump flow (Diameter) cm	Compressive strength (cylinder) MPa
	Plasticizer / Cement	fiber / Cement	Water / Cement	Gravel / Aggregate	Sand / Aggregate		
C	3%	0%	30%	55%	45%	64	44
FC1	3%	1%	30%	55%	45%	63	38.9
FC2	3%	2%	30%	55%	45%	60	37
FC4	3%	4%	30%	55%	45%	55	36

Fig. 1 The specimens were taken out of the molds and kept for 26 days in a pool

2.1 Materials

The materials used in the mixture of the prepared samples included normal Portland cement, crushed aggregates and plasticizers. A constant percentage of micro-silica fillers were also used in all samples. The SCC was prepared in two normal and fiber reinforced concrete types. The specifications of the employed polypropylene are given in Table 1.

Fiber percentage used in the concrete was the only changing parameter in the concrete mixture design (Table 2). Different fiber percentages were poured into the mold with different thicknesses in combination with normal concrete while being subjected to loads. In fact, several different samples with different combinations of normal and fiber reinforced SCCs (FR-SCC) were prepared from each mixture design and were experimented.

2.2 Specimens

90 standard cubic samples of 150 cm edge length, and 47 concrete beam samples were prepared (Fig. 1).

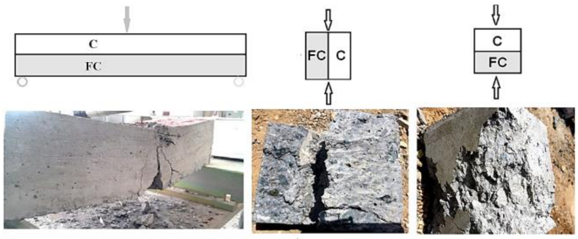

Fig. 2 Loading and direction and cracks (loadings direction on the beam samples and the cubic samples)

Compressive strength tests along two different axes (perpendicular to and in parallel with the interface of the two concrete types) were performed on the prepared concrete sample cubes at the age of 7 and 28 days (Fig. 2). The loads were applied uniformly and quasi-statically.

To assess their compressive strength, cubic samples were subjected to uniaxial loads perpendicular to and in parallel with the interface of the two concrete types. FR-SCC was first poured in the mold up to 0, 30, 50, 70 and 100 percent of its height, and normal SCC was then added. This procedure determined the interface between the normal and FR-SCCs.

2.3 Mixing and curing

The primary mixture design was simultaneously prepared in two mixers. These two mixtures were designed for the normal and FR-SCCs. In the first mixer, the aggregates and solid filler materials were mixed with cement for 1 minute. In the second mixer, polypropylene fibers were added to similar materials of the first mixer. One-third of the required water was then added to the mixture to be mixed for 1 minute. The plasticizer together with the remaining of the required water was added to the mixture. Then, with their specific recipes, the prepared materials of normal and fiber self-contacting concretes were poured into the mold in two layers with height ratios of 0, 0.5 and 0.33. The samples were allowed to harden in the mold for 24 hours, and were placed in a pool filled with limewater to cure for 26 days. The samples were then removed out of water and placed in the laboratory for 24 hours to dry.

3. Results and discussions

The behavior of fiber and normal concrete adjacent to each other is investigated in this section. The compressive strength of the cubic samples and the flexural strength of the concrete beams were assessed. The percentage of fiber reinforced concretes and the location of the interface between normal and fiber reinforced concretes were the changing factors in these experiments. Since fiber reinforced concretes exhibit better behavior under tensile loads, tensile loads are applied to those sections of the beam which are made up of fiber reinforced concretes.

Loading rate directly affects the brittleness/ductility of the concrete as well as the crack type (shear cracks or flexural cracks). These loadings were applied at rates that

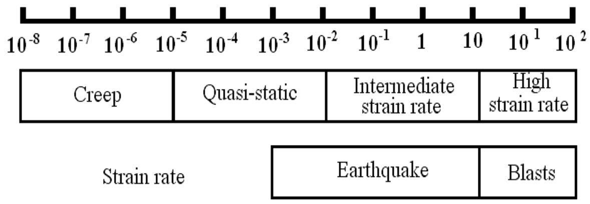

Fig. 3 Diagram of strain rate and loading type

Table 3 Compressive strength

FC/C	Cubic sample arrangement	Fiber percentage in FC: 0	1	2	4
0	C	44	---	---	---
1/2	C / FC	---	42.5	41	40.5
	FC | C	---	43.2	41.5	41
1	FC | C	---	42	40	39.8
	C / FC	---	41	39	39
2	FC | C	---	41	37	36
	C / FC	---	39	37	36
---	FC	---	38.9	37	36

Compressive Strength MPa

FC: Fiber reinforced concrete; C: Normal Concrete

were within the quasi-static region (Fig. 3). Increasing the loading rate increased the effect of fiber percentage on the concrete behavior. However, at much higher loading rates, these variation trends were reversed so that absence of fiber would not significantly affect the concrete behavior. In most cases, shear cracks were developed and little strain was observed after the peak of the loading curve. Considering the fact that a reversed trend can be obtained for the force applied to the beam, adding fiber to the perimeter of the beam can be recommended as a suitable method for improving the concrete beam behavior.

3.1 Compressive strength

The compressive strength of the cubic samples differs with respect to the added fiber percentage. Addition of fiber polypropylene results in decreased compressive strength of the concrete. This decrease in compressive strength varies based on the loading direction and the fiber percentage used (Table 3).

According to the results of compressive strength in the cubic samples, it can be understood that addition of fibers to the concrete leads to a decreased compressive strength. The loading direction as well as the direction of the interface between fiber and normal concrete types affects the compressive strength. Experiments revealed that when the

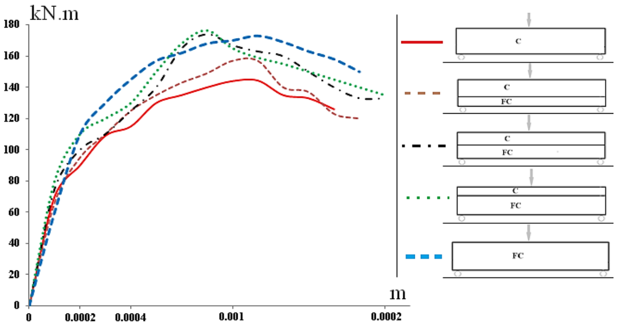

Fig. 4 Moment-curvature curve (X axis: Moment; Y axis: curve)

Table 4 Flexural tensile strength

FC/C	beam sample arrangement	Fiber percentage in FC			
		0	1	2	4
0	C	495	---	---	---
1/2	C / FC	---	540	567	578
1	C / FC	---	598	618	623
2	C / FC	---	605	615	630
---	FC	---	600	610	627

load (force) at the fracture point (N)

FC: Fiber reinforced concrete; C: Normal Concrete

loading direction was in parallel with the interface between the two concrete types, the uniaxial compressive strengths of the concrete cubes were greater.

3.2 Flexural strength

The flexural strength of normal and fiber reinforced concretes were evaluated with different fiber percentages and at different heights by conducting the three-point bending flexural tests on concrete beams. The concrete beams were of 10×20×20 cm^3 dimensions, and the fiber reinforced concrete section of the beam was placed below the beam in the tensile region. The moment-curvature diagram of the beam is demonstrated in Fig. 4.

The moment-curvature diagram of the beam with 2% fibers indicated that addition of fibers to the lower section of the beam under tensile strength decreased roughly 30% of the maximum curvature. The effect of fiber reinforced concrete height was very significant up to the middle of the beam, and was decreased as moved away towards the end of the beam. The results also suggested that the deformation in the 100% fiber reinforced concrete beam was more significant as compared with the beam made up of 30% normal concrete in the compressive section and 70% fiber reinforced concrete.

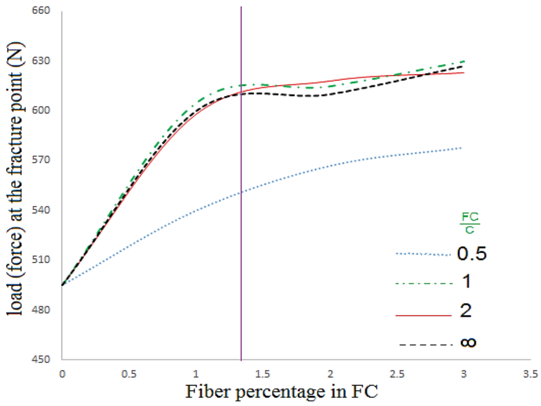

Fig. 5 Flexural failure in hybrid concrete beams containing different percentages of polypropylene

The results showed that fiber reinforced concrete is capable of withstanding more bending loads as compared with normal concrete. In addition, increases in the polypropylene fiber percentage in the tensile section increased the flexural strength of the beam. Increases in the flexural strength of the beam were more significant with addition of fibers to one-third of the tensile section region. The flexural strength significantly increased as the fiber reinforced concrete height in the beam approached the middle of the beam height. However, it should be noted that the effect of fiber reinforced concrete on the flexural strength decreased in the regions past the middle height of the beam (Table 4).

3.3 Flexural failure

According to the results, a behavioral change in the concrete beam in terms of mechanical properties (particularly bending moment) occurred when the lower half of the beam was made of the fiber-concrete mixture (Fig. 5). In the case where the lower half of the beam was made of fiber-reinforced concrete (1.4% fiber), the bending strength of the beam was increased by approximately 32% and the shear cracks were reduced. Adding fiber to the upper half of the beam also increased the beam flexural strength by about 4% (this percentage depends on the beam height and the percentage of added fiber). Examination of failure in hybrid concrete beams shows that adding fiber to the upper half of the concrete beam-which is under compression-has little effect on the flexural strength of the beam and that, before being able to exhibit its strength, the concrete fails due to three-point bending.

The best fiber-to-concrete weight ratio to use in the tensioned half of the hybrid beam for simultaneously obtaining the highest flexural strength and the lowest fiber percentage would be approximately 1.4%. For improved toughness, a fiber-to-concrete weight ratio of 1.5 was considered (Li and Deny 2007). Cao *et al.* (2014) obtained the optimum fiber percentage as 1.6. The 1.4% fiber ratio was obtained for the case where the beam was under flexural stress, and, therefore, was slightly different from the fiber percentage calculated for the case where optimum toughness was required.

5. Conclusions

The behavior of the fiber and normal self-compacting beams were investigated in the present study, and the effect of different fiber percentages were assessed in the SCC. The mechanical properties of the concrete subject to compression and bending moments were studied with quasi-static loadings. The aim of the study was to identify the behavior of compound structures made up of normal and fiber reinforced concretes. In fact, the behavior of the prepared samples made up of the two concrete types was investigated. Vibrations and movements were eliminated to prevent mixing of the two fresh concretes and achieve a clear interface between them. Therefore, the employed concretes were of self-compacting type and no vibration was required. 15 cm sample cubes were prepared with different ratios of fiber and normal concretes, and were subject to loadings in directions perpendicular to and in parallel with the interface between the two concrete types. The results indicated that compressive strengths of the sample cubes were higher when the loading direction was in parallel with the interface. With increases in the amounts of fiber, the effect of loading direction on the compressive strength of the cube decreased in both perpendicular and parallel directions. Concrete beams with dimensions of $20\times20\times100$ cm^3 were used to study the bending behavior. Fiber and normal concretes were used in the concrete beams adjacent to each other at different height ratios. Fiber reinforced concrete was used in the lower part of the beam in the tensile section. The results of the three-point bending flexural test indicated that the fiber reinforced concrete beam could withstand greater maximum bending moment with less curve. However, the compound beams with fiber reinforced concrete in the tensile section and normal concrete in the other half demonstrated a better behavior. It can be concluded from the present study that normal SCCs and FR-SCCs may be used alongside each other both in structures and structural members. Moreover, no separation was observed in the interface between the two concrete types, neither in the cubic samples subject to compression nor in the concrete beams subject to bending moments.

Acknowledgments

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