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PROPERTIES OF CEMENT-GROUTED SAND WITH DISTANCE FROM INJECTION

PROPRIETES DES SABLES INJECTES AU CIMENT EN FONCTION DE LA DISTANCE AU POINT D'INJECTION

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SYNOPSIS : Three microfine cement grouts at different water-to-cement ratios were injected into columns of a medium fine sand, and the strength and permeability were determined at various distances from the injection point. The rheology of the grout is influenced by the type of mixer used, and this, in turn, plays a role in the injectability of the grout and the resulting uniformity of the mechanical properties of the grouted soil.

INTRODUCTION

The injection of a particulate grout into a soil and the resulting improvement in the mechanical properties of the soil are a function of the type of grout, the concentration of the suspension, and the type of mixer used. More specifically, the variation in the permeability and strength of the grouted soil with distance from the point of injection is influenced by the rheology and bleed characteristics of the grout, which are, in turn, affected by the type of mixer used.

OBJECTIVES

The primary objectives of this study are (a) to assess the relative injectability and effectiveness of three different microfine cement grouts at several different water-to-cement ratios by measuring the changes in the permeability and strength of the grouted soil with distance from the point of injection and (b) to determine the effect of mixer type (including both laboratory and field mixers) on the magnitude of the improvement obtained and the variation of grouted soil properties. A secondary objective is to relate the rheological behavior of microfine cement grouts to their injectability and effectiveness in improving the mechanical properties of the soil.

SANDS AND CEMENTS

Two locally available sands (Torpedo I and II) were each custom-blended, utilizing only that portion of the sand passing the #20 sieve and retained on the #200 sieve. The grain size distributions of these sands are shown in Figure 1 and can be seen to be quite similar. Also shown in Figure 1 are the grain size distributions of the three microfine cements used in this study. These are MC-100 (a microfine slag cement marketed by Geochemical Corporation of Ridgewood, New Jersey), MC-300 (a microfine Portland cement obtained from Heracules International in Athens, Greece), and MC-500 (a blend of slag and Portland cements manufactured by the Onoda Cement Company of Japan). The MC-300 and MC-500 grout suspensions contained 1% (by dry weight of cement) of NS-200 (a naphthalene sulfonate formaldehyde condensate) to decrease interparticle forces and enhance more complete wetting and mixing of the cement particles. In the case of MC-100, CA-600 (a polymer of acrylic acid) was used instead of NS-200 and 5% sodium hydroxide (by dry weight of cement) was included to accelerate setting.

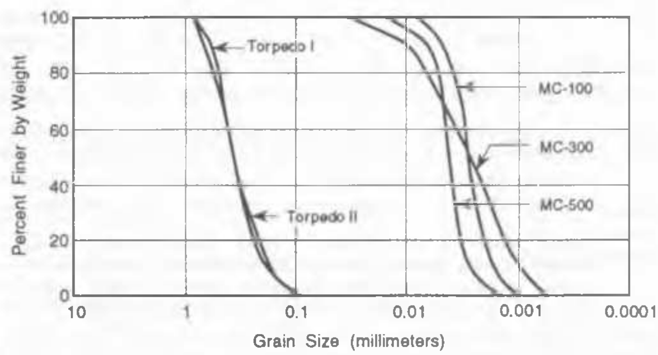

Figure 1. Grain Size Distributions of Sands and Cements

MIXERS AND MIXING PROCEDURE

Three different types of mixers were used to prepare the grout. The first was a laboratory-size paddle mixer (manufactured by Mixing Equipment Company of Rochester, New York), which caused a stirring action within the suspension by means of a propeller with a diameter about one-third the diameter of the drum. This mixer was operated for 2 minutes at a rotational speed of 50 rpm with a batch volume of 1 liter (thus imparting an "energy density" of about 100 rpm per liter of fluid). The second was a standard blender (Oster Model 460-01), which had an estimated rotational speed of 5,000 to 10,000 under load. Mixing times were 1 minute for a batch volume of 0.65 liter (for an "energy density" of about 7,700 to 15,300 rpm per liter of fluid). The third was a commercially available field-size Colcrete mixer (Model SD4 manufactured by Colcrete in England), which had a rotational speed of 1500 rpm. Batch volumes of 80 liters were mixed for 1 minute (imparting an "energy density" of about 20 rpm per liter of fluid).

The latter two mixers may be termed high speed mixers because of the high rotational speeds and generally small tolerances between the rotor and the housing. High speed mixers generally cause the formation of a vortex which acts as a centrifugal separator to break apart aggregations of particles and thereby enhance a more thorough wetting of cement grains. The shearing action imparted by any given mixer will depend on the rotational speed of the mixer, the mixing duration, the batch volume, and the concentration (or number) of cement particles in the mix; as the number of cement particles increases with decreasing water-to-cement ratio of the grout, the number of interparticle collisions will increase. While it is recognized that the specific energy imparted to the mix will be influenced by the physical size of the mixing drums, rotors, and tolerances between the respective rotor and housing, these parameters were not addressed in this study. Regardless of the water-to-cement ratio, the total volume of grout per batch was nominally constant for a given mixer. The dispersant NS-200 was first mixed thoroughly with the mixing water; then, the microfine cement was added and the suspension was mixed for the designated time. In the case of MC-100, the dispersant CA-600 and NaOH catalyst were mixed first with the water, after which the cement was added.

SPECIMEN PREPARATION

Grouted sand specimens were prepared by placing Torpedo sand at a dry density of 1.84 ± 0.03 Mg/m^3 in PVC tubes 5 cm in diameter and 60 cm (24 inches) long. When packing the column, a #20 mesh screen was first placed on the bottom, after which was placed a filter consisting of a 2.5-cm layer of pea gravel followed by an additional 2.5-cm layer of #4-10 coarse sand. Dry #20-200 Torpedo sand was then dropped into the column through a funnel positioned at the top with a hose extending into the column to minimize the separation of fine and coarse sand particles. When the height of the sand reached approximately 15 cm, the sand was densified by placing a 13-N weight inside the column and tapping the wall of the column at the level of the sand layer with a small hammer at three points spaced 120° apart. Successive layers of sand were placed in this manner until the column was filled to about 5 cm from the top. Then, a filter and a mesh screen similar to the one at the bottom was placed at the top of the sand; finally, the top cap was secured to the column.

The sand was saturated by an upward flow of tap water through a valve located near the bottom of the column under a pressure of approximately 28 MPa. Water was allowed to flow through the column for approximately 30 minutes, after which the permeability of the sand in the column was determined by the flow measured during the next 10 minutes. The nominal permeability of the sand columns was 0.023 cm/sec. A maximum grouting pressure of 386 MPa was used to inject the grout and flow rates did not exceed 6 ml/sec. To avoid sedimentation of the grout prior to injection, the suspension in the grout supply tank was stirred continuously by a specially installed propeller. Grouting was continued until a volume of fluid equal to twice the void volume of the sand column was collected at the outlet of the column or until the flow of effluent ceased under the maximum grouting pressure. Unique to grouts prepared by the blender, three separate batches of 0.65 ml each were required to achieve the necessary grout volume for injection. During the mixing of consecutive batches, the grout previously mixed underwent continuous agitation by a paddle mixer rotating at 50 rpm. This procedure allowed the entire volume of grout to be prepared in about 3.5 minutes, during which time there were insignificant changes in the rheology of the grout (Schwarz and Krizek, 1992).

After grouting was completed, the column was stored vertically for approximately 48 hours to allow the grout to set; then, the column was submerged in water for the duration of the curing period (7 days or 48 days). The cured grouted column was cut into four 10 cm long sections, and each was tested to obtain the coefficient of permeability and the unconfined compressive strength of the grouted sand. Constant head permeability tests were conducted under a hydraulic gradient ranging from about 11 to 16 in specially constructed permeameters without removing the grouted sand sample from the PVC tube. Following the permeability test, the PVC tube was slit longitudinally, the specimen was removed, the ends were capped, and an unconfined compression test was conducted with times-to-failure on the order of 1 to 1.5 minutes.

RHEOLOGICAL BEHAVIOR OF GROUTS

Cement suspensions may be categorized as Bingham fluids, which are characterized by a yield stress and viscosity. Depicted in Figure 2 are typical flow curves A and B for a Newtonian fluid (such as water) and a Bingham fluid (such as cement grout), respectively. In general, a viscometric measurement on a non-Newtonian fluid represents the rheologic behavior for only one point on the flow curve, and the viscosity so determined is called the apparent viscosity, η_a, because the interpretation of the data is based on the implicit assumption of a Newtonian fluid. Of course, a series of measurements at different strain rates will readily reveal that the "apparent viscosity" is strain dependent and therefore the fluid is really non-Newtonian and perhaps Bingham in nature. Assuming the latter case, the plastic viscosity, η_p, is defined as the slope of the flow curve as the strain rate approaches infinity and the yield stress, τ_y, is that stress which must be exceeded before flow commences.

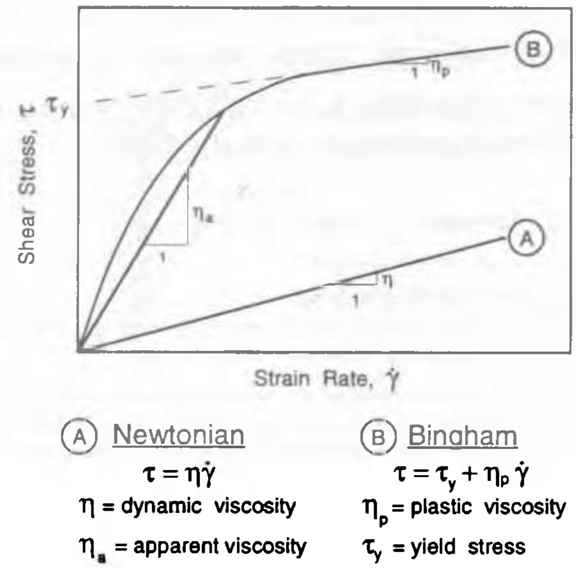

Figure 2. Parameters for Different Rheologic Materials

Table 1 gives comparative values for the apparent viscosity measured 1 minute and 10 minutes after mixing was completed for the microfine cements prepared by the various mixers; these data are based on the assumption of a Newtonian fluid tested at a strain rate of about 50 sec^{-1}. As expected, the viscosities for the 1:1 mixes are considerably higher than those of the 2:1 and 3:1 mixes. In general, MC-100 exhibited the lowest viscosity and MC-300 exhibited the highest. Viscosities increased during the 10-minute interval of measurement; viscosities for 1:1 mixes increased up to three-fold, whereas viscosities for 2:1 and 3:1 mixes increased two-fold or less. Generally, the Colcrete-mixed grouts had lower viscosities than grouts mixed by the blender and paddle mixer, the most significant effect being observed for MC-300 grouts.

Table 1. Apparent Viscosities for Microfine Cement Grouts

Cement	MC-100			MC-300			MC-500		
Water:Cement Ratio	1:1	2:1	3:1	1:1	2:1	3:1	1:1	2:1	3:1
Mixer	Values obtained after 1 minute								
Paddle							45	3+	2
Blender	50	3	2	1000	160	15	50	3+	2
Colcrete	30	4	2	100	22	16	55	4	3
Mixer	Values obtained after 10 minutes								
Paddle								6	2+
Blender	60	2+	2	1000+	180	15	150	5+	2+
Colcrete	35	4	2+	140	40	30	175	6	3

An extended analysis of the flow behavior of the above suspensions, based on the assumption of a Bingham fluid, gives the properties summarized in Table 2. The effect of mixer type on the plastic

Table 2. Plastic Viscosity and Yield Stress for Microfine Cement Grouts

Water: Cement Ratio	Blender-Mixed MC-100		Paddle-Mixed MC-500		Blender-Mixed MC-500		Colcrete-Mixed MC-500	
	Yield Stress (mPa)	Plastic Viscosity (mPa•s)	Yield Stress (mPa)	Plastic Viscosity (mPa•s)	Yield Stress (mPa)	Plastic Viscosity (mPa•s)	Yield Stress (mPa)	Plastic Viscosity (mPa•s)
1:1	385	79			640	75	340	81
2:1	20	79	70	79	90	79	70	81
3:1	5	76	25	76	40	75	40	79

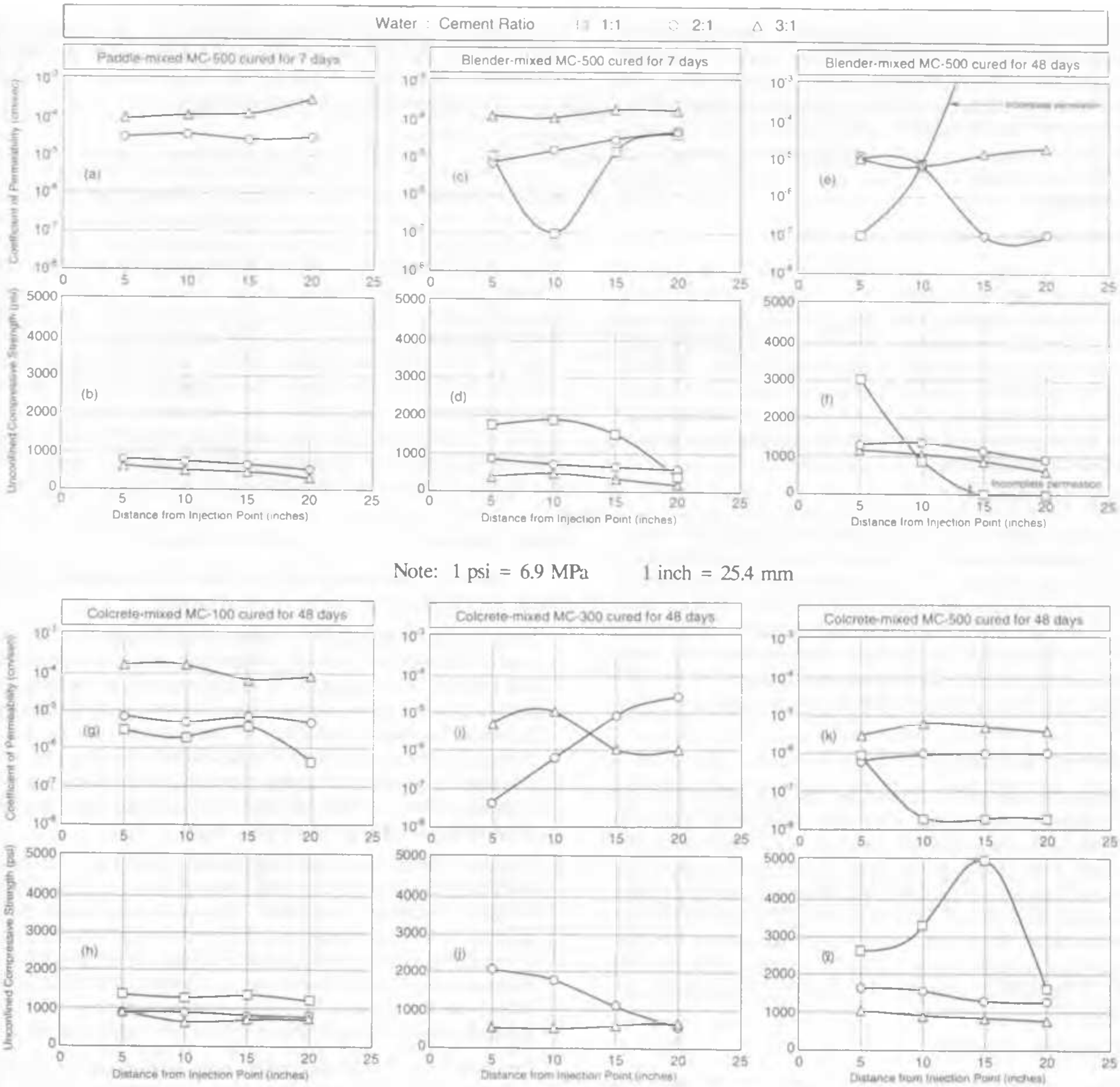

Figure 3. Changes in Permeability and Strength with Distance from Injection Point for Different Grout

viscosity of MC-500 grouts is not significant, but slightly lower plastic viscosities were determined for blender-mixed MC-500 grouts compared to their Colcrete-mixed counterparts. A comparison of the yield stress for MC-500 grouts shows that the Colcrete mixes have significantly lower values than the blender-mixed grouts – as much as 50% lower for 1:1 mixes. Compared to their blender-mixed couterparts, MC-500 grouts prepared by the paddle mixer exhibited similar plastic viscosities and somewhat lower yield stresses. In the case of MC-100 and MC-500 grouts prepared by blender mixing the MC-100 yield stresses were 40% and 85% lower for 1:1 to 3:1 mixes, respectively, but the MC-100 plastic viscosities were similar to those of the MC-500 grouts.

RESULTS FROM PERMEABILITY AND STRENGTH TESTS

The data presented in Figure 3 suggest that the effectiveness of grouting may decrease somewhat with increasing distance from the injection point. While it is recognized that the resulting mechanical properties of grouted sand may be influenced significantly by the type, gradation and density of the soil being grouted, the type, water-to-cement ratio and processing (mixing) of the grout used, and the total volume of grout injected, a comprehensive investigation of all factors was beyond the scope of this study. In particular, the effects of the first two parameters were eliminated from this investigation by filling each injection column with the same sand placed at essentially a constant density and injecting a constant volume of grout equal to twice the void volume of the sand; deviations from the foregoing situation occurred when injecting MC-500 1:1 grout (whereby flow ceased under the maximum grouting pressure of 386 MPa) and MC-300 1:1 grout (which was unable to permeate farther than the first 10 cm of the sand).

Blender-mixed and Paddle-mixed MC-500 Grout

Specimens injected with either blender-mixed or paddle-mixed MC-500 2:1 or 3:1 grouts and cured for 7 days manifested no significant differences in permeability or strength. In general, the permeability of the ungrouted sand was reduced by about one, two, and four orders of magnitude when injected with 3:1, 2:1, and 1:1 grouts, respectively. The unconfined compressive strengths of specimens grouted with 2:1 and 1:1 mixes were about two and four times greater than that for the 3:1 mix.

When cured for 48 days, the permeability decreased approximately five orders of magnitude for 1:1 and 2:1 mixes and three orders of magnitude for 3:1 mixes, relative to the permeability of the ungrouted sand. The unconfined compressive strengths of 48-day specimens increased 40% to 180% relative to the 7-day strengths, the most significant increases being exhibited by the 3:1 mixes. However, in the case of the 1:1 mixes it was extremely difficult to maintain the flow quantity needed to achieve successful permeation.

Colcrete-mixed MC-500 Grout

Specimens injected with Colcrete-mixed MC-500 1:1, 2:1, and 3:1 grouts and cured for 48 days exhibited permeabilities approximately six, five, and four orders of magnitude lower than that of the ungrouted sand; these are about one order of magnitude lower than those of comparable specimens injected with blender-mixed or paddle-mixed grouts. Similarly, the unconfined compressive strengths of specimens injected with Colcrete-mixed grouts were generally higher (up to 70%) than their blender-mixed counterparts, larger increases being measured for specimens injected with lower water-to-cement ratio grouts.

Colcrete-mixed MC-100 Grout

Specimens injected with Colcrete-mixed MC-100 3:1, 2:1 and 1:1 grouts yielded permeability values two to four orders of magnitude lower than that of the ungrouted sand. A comparison of permeability values for specimens injected with Colcrete-mixed MC-100 or MC-500 grout shows that those grouted with MC-500 generally attained permeabilities up to two orders of magnitude lower for identical water-to-cement ratio mixes. Strength comparisons show MC-500 grouted specimens are 20% to 115% stronger than MC-100 grouted specimens for 3:1 and 1:1 mixes, respectively.

Colcrete-mixed MC-300 Grout

Specimens injected with Colcrete-mixed MC-300 3:1 and 2:1 mixes exhibited permeability reductions of four orders of magnitude relative to the permeability of the ungrouted sand; however, the 1:1 mix was unable to permeate any measureable distance into the injection columns. The permeabilities of specimens grouted with MC-500 were similar to an order of magnitude lower than those of MC-300 grouted specimens for identical water-to-cement ratios. In general, the unconfined compressive strengths of MC-500 grouted specimens were higher than those of their MC-300 counterparts, being approximately 50% and 15% higher for 3:1 and 2:1 mixes, respectively.

Strength-Permeability Correlation

Figure 4 shows the correlation between the strength and permeability for all tests; the plotted values represent the geometric mean of the results obtained for the four specimens from each column. Also shown are data reported by Zebovitz, Krizek, and Atmatzidis (1989) for paddle-mixed MC-500 grout injected into larger columns of a slightly coarser Torpedo sand than depicted in Figure 1.

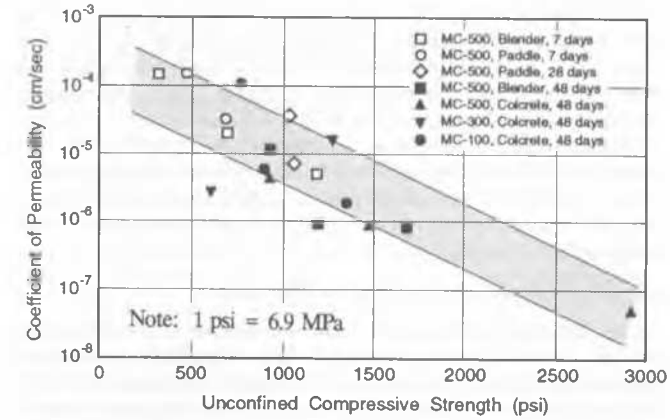

Figure 4. Correlation between Strength and Permeability

Effect of Grout Rheology

Grout mixes with water-to-cement ratios of 2:1 and higher have apparent viscosities less than 6 cp (cp = mPa·s) and were able to successfully permeate the sand in the injection columns (an exception was the MC-300 grout, whereby permeation was not uniform, as evidenced by three orders of magnitude variation in permeability over the length of the column). Grouts with a water-to-cement ratio of 1:1 have a 1-minute apparent viscosity of about 50 cp or more, and it was generally more difficult to inject these mixes. The yield stress and plastic viscosity are measures of the stresses required to start the grout flowing and to maintain the flow, respectively. This suggests that the observed improvement in the injectability and mechanical properties of the specimens injected with Colcrete-mixed grouts compared to those injected with blender-mixed or paddle-mixed grouts may be attributable in large part to the decrease in the yield stress of the Colcrete-mixed grouts.

CONCLUSIONS

Based on the results obtained from the experiments reported herein, the following conclusions can be advanced.

1. Sand injected with microfine cement grouts prepared in a Colcrete mixer exhibited more uniformity of soil properties with distance from the injection point compared to grouts prepared in the blender or paddle mixers. Sand injected with Colcrete-mixed MC-500 grout exhibited the largest reduction in permeability and the greatest increase in strength compared to sand injected with grout prepared in a blender or paddle mixer. Sands grouted with smaller-particle-size microfine cement grouts exhibited more uniformity in mechanical properties over the injected column length.
2. The type of microfine cement (particle size, percent slag, and percent Portland) influences the properties of the grouted soil and the degree of their development with time. This is because smaller cement particles hydrate at a faster rate than larger particles, and therefore permeability reductions and strength increases develop earlier. The hydration rate of slag cement is slower than that of Portland cement; hence, microfine cements composed of greater percentages of slag will generally require a longer time to develop comparable strengths.
3. The yield stress of microfine cement grout is influenced by mixer type and cement type, and it appears to play a large role in the injectability of a grout and the resulting uniformity in the mechanical properties of the grouted soil. Apparent viscosity, on the other hand, is not a sufficient criterion for anticipating the injectability of microfine cement grout, although it may be indicative of early flocculation and subsequent sedimentation tendencies (also influenced by mixer and cement type).

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