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An Experimental Study on Shear Strength of Cemented Paste Backfill Materials

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Abstract: Change in the mechanical parameters of cohesion and internal friction angle with variations in cement content and curing time of cemented paste backfill (CPB) materials was investigated carrying out a series of experimental study. In this scope, shear strength and uniaxial compressive strength (UCS) tests were performed to find out the failure properties of CPB samples. According to the results obtained from this study, a new factor is suggested to use in the Mohr-Coulomb failure criterion to better fit the envelope for CPB materials. As an important issue from this study, strength values of curing CPB specimens were found to dominantly increase because of the improvement in cohesion values instead of internal friction angle. With an increase in cement content, strength values were measured to increase because of the improvement in both internal friction angle and cohesion parameters. Additionally, start of decrease in strength values due to the sulphate attack was found be postponded as another advantage of the increase in cement content.

Çimentolu Macun Dolgu Malzemelerinin Makaslama Dayanımı Üzerine Deneysel Bir Çalışma

Anahtar Kelimeler
Makaslama dayanımı,
Mekanik parametreler,
Çimentolu macun dolgu,
Maden dolgusu,
Yeraltı madenleri

Özet: Bu çalışmada, çimento miktarı ve kür süresinin madencilikte kullanılan çimentolu macun dolgu malzemelerinin kohezyon ve içsel sürtünme açısı değerleri üzerindeki etkileri bir dizi deneysel çalışma ile incelenmiştir. Macun dolgu malzemelerinin yenilme özelliklerinin belirlenmesi için makaslama ve tek eksenli sıkışma dayanımı testleri gerçekleştirilmiştir. Elde edilen sonuçlara göre, Mohr-Coulomb yenilme ölçütünün çimentolu macun dolgu malzemeleri için kullanımına yönelik yeni bir katsayının kullanımı önerilmiştir. Çalışmanın önemli çıktılarından bir diğeri olarak, kür süresinin artışı neticesinde dayanım değerlerindeki iyileşmenin içsel sürtünme açısı nedeni ile değil, baskın olarak kohezyon değerlerindeki artıştan kaynaklandığı belirlenmiştir. Çimento miktarındaki artış sebebi ile hem içsel sürtünme açısı hem de kohezyon değerlerinde artış olduğu görülmüştür. Ayrıca, sülfat atak kaynaklı dayanım değerlerindeki azalmanın çimento miktarındaki artış neticesinde gecikerek daha uzun kür sürelerinde yaşandığı belirlenmiştir.

1. Introduction

Because of environmental issues and economical reinforcement necessities in underground mining operations, cemented paste backfill (CPB) applications have gained popularity, in last years. CPB is a type of underground mine reinforcement which generally consists of mineral processing plant tailings, cement and water. As a result of need for convenient workability of the mix with the fine mine tailings, CPB has much higher ratio of water to cement in comparison with widely applied concrete materials. Water to cement ratio changes in a range from 3.0 to 5.0 based on the characteristics of CPB components. In general, more than 90% of the solid content of CPB is the tailings [1-4].

Since the fresh paste backfill is pumped to the underground stopes, its rheology is a critical factor for material transportation. The fresh mix pumped to the underground stopes behaves like a non-newtonian fluid which flows by applying an external

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stress [5, 6]. Based upon the drainage of water, solid content in a unit volume increases as the CPB mixes are consolidated in stopes. Therefore, the mechanical properties of CPB mixes can be investigated in accordance with different approaches for fluids and solids. It should be noted that solid stage mechanics of CPB materials can also be classified as saturated soil mechanics for fresh mixes before curing and concrete mechanics for the cured material [7-10].

Strength values of CPB changes in accordance with many parameters such as cement content, tailings mineralogy and particle size distribution, curing time, underground water condition, drainage conditions, stope dimensions and filling application details changing the consolidation conditions. Because CPB is not applied for the aim of supporting the roof load, its target strength after curing reactions should be enough for being stable under its self-weight. Generally, uniaxial compressive strength of 1 MPa is found to be adequate in typical sub-level caving and cut and fill mines which have stope heights less than 15 meters [11-14].

Strength values of solid materials depend on the mechanical parameters of cohesion and internal friction angle. Changes in strength values can be explained by the change in cohesion and internal friction angle [15, 16]. In this study, cohesion and internal friction angle of different CPB mixes were determined to investigate their effect on shear strength, compressive strength values. Within this purpose, cohesion and internal friction angle changes were separately examined for different cement contents and curing times. Additionally, relations between shear strength and uniaxial strength values were investigated for different CPB mixes with varying curing times.

2. Materials and Methods

Mineral processing plant tailings of Cayeli copper mine was investigated in this experimental study. Particle size distribution of the tailings was determined by using a laser particle size analyser, Malvern Mastersizer Hydro 2000 MU. Based on the particle size distribution [3], approximately 88% of the tailings has silt particle size (2-63 μm), and about 12% of the tailing has clay particles (<2 μm). Therefore, the tailings can be classified as a silt type material. The fines content (-20 μm) of the tailings is about 56% where a minimum of 15% fine particles is required for the colloidal characteristics. The tailings is rich of pyrite minerals where the amount of such minerals is 76% based on the chemical analysis. The extensive characterization of the tailings material can be found elsewhere Cihangir et al. [3]. Some details for particle size distribution analyses of the mine tailings, the coefficient of curvature (C_c) and the coefficient of uniformity (C_u) are given in Table 1. A CEM I type ordinary Portland cement product was used with tap water in this experimental study.

To prepare CPB mixes, tailings material, cement and tap water were homogenized in a concrete mixer for ten minutes. Before moulding CPB mixes, workability of fresh materials was evaluated carrying out the slump test (Figure 1). CPB mixtures were prepared at 7.5±0.3 inch slump values. Thereafter, mixtures were cast into the cylindrical moulds manufactured for uniaxial compressive strength (UCS) and shear strength tests.

The UCS test specimens were cast into the moulds with the ratio of height to diameter of 2 where the diameter is 10 cm. The UCS specimens were cast in three steps and compacted using tamping rods to remove air in the fresh mix after each casting steps (Figure 2). Similarly, shear strength test specimens were compacted with the tamping rods after being cast into the moulds with a height of 2.5 cm and a diameter of 6.3 cm. The drilled bottoms of both UCS and shear strength test moulds allowed the bleed water drainage. Conventional soil shear box equipment and a sensitive electric motor loading press for soil materials were respectively used to determine shear strength and UCS values (Figures 3 and 4). To determine internal friction angle and cohesion, triple specimens were tested under each three different normal load values, eight different curing time and three different cement content conditions. Loading rate was selected as 0.35 mm/min for shear strength test specimens and 0.5 mm/min in the UCS tests.

Strength tests were performed on the CPB specimens with different curing times of 3, 7, 14, 28, 56, 112, 224 and 360 days. Totally, 216 shear strength specimens and 72 UCS specimens were prepared and cured at 20 ± 1 °C temperature and 80 ± 1% humidity for the different periods up to 360 days. Three different mixes with different cement percentages of 5%, 6% and 7% in solid content (tailings+cement) were tested in the experimental studies. In Table 2 showing the content of the mixes, percentages in the specimens are given by weight.

Considering variations of UCS and shear strength values with changing mechanical parameters of cohesion and internal friction values, Mohr&Coulomb failure criterion was investigated whether it fits for CPB materials in this study. According to the Mohr&Coulomb failure criterion, changes of shear strength and UCS values depending on cohesion and internal friction angle are respectively seen in Equation 1 and Equation 2. In the equations, c is cohesion (kPa), ϕ is internal friction angle (°), τ is shear strength (kPa) and σ_n is normal stress applying on specimen (kPa).

$$\tau = c + \sigma_n tan\phi \quad (1)$$

$$UCS = 2c\sqrt{(1+\sin\phi)/(1-\sin\phi)} \quad (2)$$

Figure 1. Slump test for CPB mixes

3. Results

The slump value of the paste mixtures was measured to be between 7.2 inch and 7.8 inch, which is the most frequently used slump value interval of fresh material in CPB operations [17-20]. UCS and shear strength test results for different curing times are given in Table 3 and Table 4, respectively. Additionally, UCS values are schematically given in Figure 5. Because UCS specimens with the curing times of 3 days and 7 days were broken during the removing from moulds, they could not be tested. In Tables 5 and 6, cohesion and internal friction angle values calculated from the results of shear strength tests are given for different cement contents and curing times. As parallel to the Mohr&Coulomb failure criterion, a linear increase of shear strength with an increase in the compressive stress was found practically acceptable to fit for tested CPB materials (Figure 7). However, it was seen that the Mohr circle approach to calculate uniaxial compressive strength values according to the Mohr&Coulomb failure criterion, which is given in Equation 2 was found to be not consistent with the results obtained from the UCS test (Figure 6). UCS values calculated with Equation 2 (UCS_i) are given in Table 7. As seen in Equation 3, a factor called *n* is suggested to use with Equation 2 for better prediction of the relation between UCS values and the mechanical properties of cohesion and internal friction angle. To calculate *n* values given in Table 8, cohesion and internal friction angle values obtained from shear strength test and UCS test results were inserted in Equation 3.

$$UCS = \left(2c\sqrt{(1+\sin\phi)/(1-\sin\phi)}\right)n \qquad (3)$$

Table 1. Particle size distribution data for tailings used in this study (D_{10}, D_{30} and D_{60} are 10%, 30% and 60% passing particle sizes, respectively)

D_{10} (μm)	D_{30} (μm)	D_{60} (μm)	C_u	C_c
2	8	26	13.0	1.23

Figure 2. Specimen preparation: a) mixing, b) molding, c and d) compaction with the tamping rods, e) surface flattening

Figure 3. UCS test: a) a specimen under load, b) a failed specimen

Table 2. Contents of different mixes

Specimen type	Cement (wt.%)	Water (wt.%)	Tailings (wt.%)
PB5	3.85	23.0	73.15
PB6	4.62	23.02	72.36
PB7	5.39	23.05	71.56

Table 3. UCS test results

Strength value explanation	14 days	28 days	56 days	112 days	224 days	360 days
PB5 Specimen 1 UCS (MPa)	0.53	0.64	0.68	0.66	0.56	0.38
PB5 Specimen 2 UCS (MPa)	0.55	0.65	0.68	0.68	0.59	0.38
PB5 Specimen 3 UCS (MPa)	0.53	0.66	0.69	0.66	0.58	0.40
PB5 Mean UCS (MPa)	0.54	0.65	0.68	0.67	0.58	0.39
PB6 Specimen 1 UCS (MPa)	0.69	0.87	1.07	1.12	1.07	0.95
PB6 Specimen 2UCS (MPa)	0.68	0.86	1.06	1.10	1.05	1.00
PB6 Specimen 3 UCS (MPa)	0.70	0.89	1.05	1.11	1.08	0.97
PB6 Mean UCS (MPa)	0.69	0.87	1.06	1.11	1.07	0.97
PB7 Specimen 1 UCS (MPa)	0.87	1.12	1.37	1.43	1.44	1.37
PB7 Specimen 2UCS (MPa)	0.89	1.10	1.35	1.44	1.45	1.38
PB7 Specimen 3 UCS (MPa)	0.90	1.13	1.38	1.43	1.43	1.37
PB7 Mean UCS (MPa)	0.89	1.12	1.37	1.43	1.44	1.37

Table 4. Shear strength test results (0.17, 0.24 and 0.30 respectively represent specimens loaded under 0.17 MPa, 0.24 MPa and 0.30 MPa normal stress. Triple specimens were tested for each mean value)

Strength value explanation	3 days	7 days	14 days	28 days	56 days	112 days	224 days	360 days
PB5-0.17-SS (kPa)	125	141	170	179	193	168	149	113
PB6-0.17-SS (kPa)	136	152	188	211	224	233	215	187
PB7-0.17-SS (kPa)	141	168	202	223	249	282	310	293
PB5-0.24-SS (kPa)	160	177	191	204	218	185	153	116
PB6-0.24-SS (kPa)	169	192	213	239	274	262	248	212
PB7-0.24-SS (kPa)	176	205	226	252	278	312	337	321
PB5-0.30-SS (kPa)	198	211	220	225	237	209	175	130
PB6-0.30-SS (kPa)	212	220	235	266	282	288	273	233
PB7-0.30-SS (kPa)	221	234	256	278	300	345	364	297

Table 5. Cohesion values for different mixes

	3 days	7 days	14 days	28 days	56 days	112 days	224 days	360 days
PB5	25 kPa	42 kPa	105 kPa	120 kPa	130 kPa	119 kPa	114 kPa	89 kPa
PB6	27 kPa	70 kPa	115 kPa	125 kPa	140 kPa	147 kPa	138 kPa	132 kPa
PB7	30 kPa	80 kPa	135 kPa	155 kPa	185 kPa	200 kPa	235 kPa	220 kPa

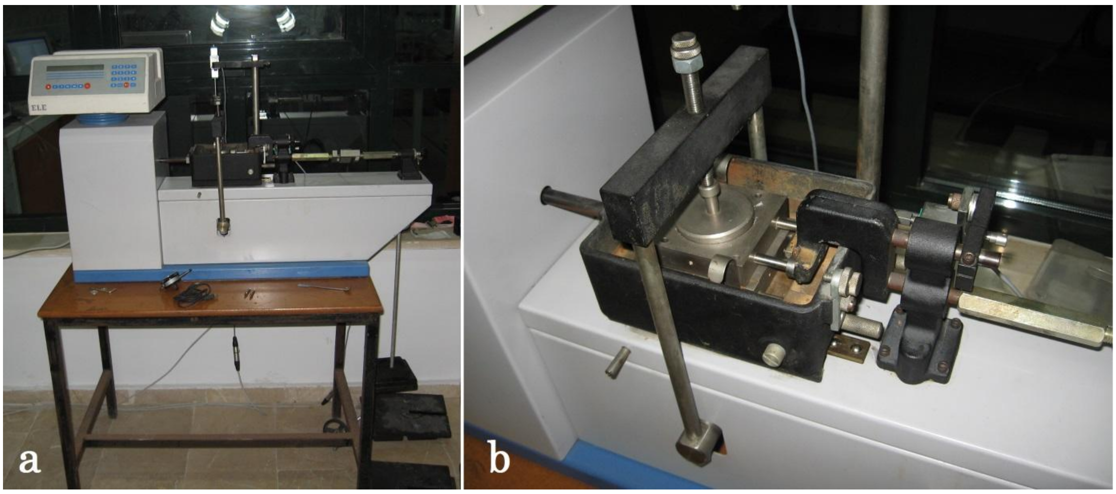

Figure 4. Shear strength test: a) Shear test machine, b) a view of shear box part of the machine

Table 6. Internal friction angle values

	3 days	7 days	14 days	28 days	56 days	112 days	224 days	360 days
PB5	30°	29°	21°	19°	20°	17°	11°	7°
PB6	31°	28°	22°	24°	24°	23°	23°	18°
PB7	31°	27°	21°	23°	22°	24°	24°	22°

Table 7. UCS values calculated considering cohesion and internal friction angle (UCS_i)

	3 days	7 days	14 days	28 days	56 days	112 days	224 days	360 days
PB5	87 kPa	142 kPa	306 kPa	338 kPa	371kPa	321 kPa	276 kPa	201 kPa
PB6	96 kPa	233 kPa	339 kPa	391 kPa	438 kPa	455 kPa	427 kPa	372 kPa
PB7	107 kPa	260 kPa	394 kPa	468 kPa	546 kPa	626 kPa	727 kPa	664 kPa

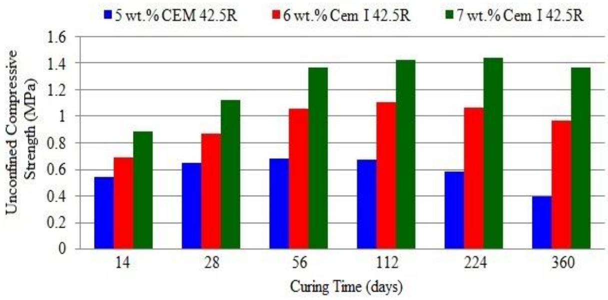

Figure 5. UCS values for different curring time and cement contents

4. Discussions and Conclusion

As air penetrates into the voids of CPB materials, oxidation of pyrite mineral becomes fast by causing alteration of the hydration products. Therefore, strength values of the CPB materials started to decrease after a period for the sulphate attack occurrence induced in the presence of pyrite mineral contacting to air and water [21-25]. It was seen in this study that the start of decrease in strength values due to the sulphate attack is later for CPB mixes with higher cement content in comparison with the mixes having low content of cement. This situation is a significant advantage of high amount of cement use in the mixes for having longer service lifetimes.

It was seen that cohesion values were found to increase with an increase in the curing time until the sulphate attack is started, whereas a general decrease in internal friction angles was observed with the increase in curing time. Results also suggest that internal friction angle has a dominant role in gaining of strength of fresh CPB materials considering the lower cohesion values in the early ages.

The decrease in internal friction angle was found more notable for low cement ratio than that in use of high cement ratio. As low as 7° internal friction angle was measured from 360 days curing CPB specimens with 5% cement ratio. According to the results of this study, sulphate attack was also found to be an important reason for excessive decrease in internal friction angle values. In spite of the strength decrease owing to the sulphate attack, it should be noted herein that service lifetimes of the CPB mixes in mine stopes are generally not longer than the period for the start of sulphate attack as mining operations are already carried out in the vicinity. Because of low strength values of CPB mixes, they are not a filling to support roof. Instead of being a support material, target strength values of CPB mixes are generally defined to be stable under its self-weight [5, 15, 26, 27].

UCS values calculated in accordance with Equation 2 were not assessed to be consistent with UCS test results in this study. Therefore, the classical Mohr&Coulomb criterion was not found to be a representative model for CPB materials for compressive strength evaluation by considering cohesion and internal friction angle values. The ratio between direct UCS values and indirect UCS values calculated from Equation 2 (UCSi), which is the *n* value in Equation 3 was seen to change from 1.8 to 2.6 in this study.

Table 8. Ratios of UCS values determined with cohesion and internal friction angle (UCS_i) to UCS test results (*n*)

Strength value explanation	14 days	28 days	56 days	112 days	224 days	360 days
PB5 UCS/ UCS_i	1.8	1.9	1.8	2.1	2.1	1.9
PB6 UCS/ UCS_i	1.8	2.2	2.4	2.4	2.5	2.6
PB7 UCS/ UCS_i	2.3	2.4	2.5	2.3	2.0	2.1

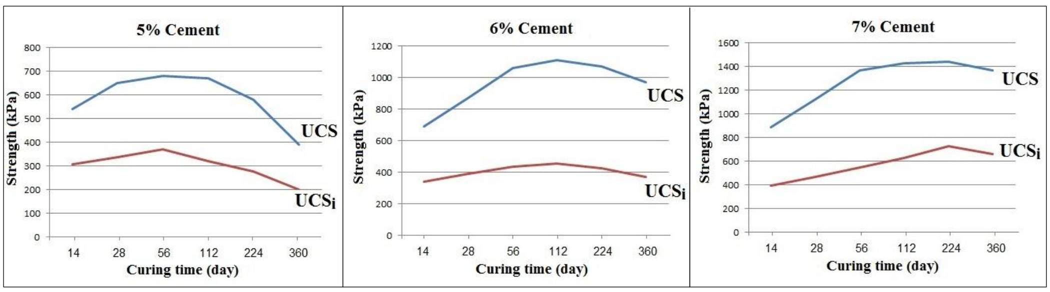

Figure 6. UCS and UCS_i values for different CPB mixes

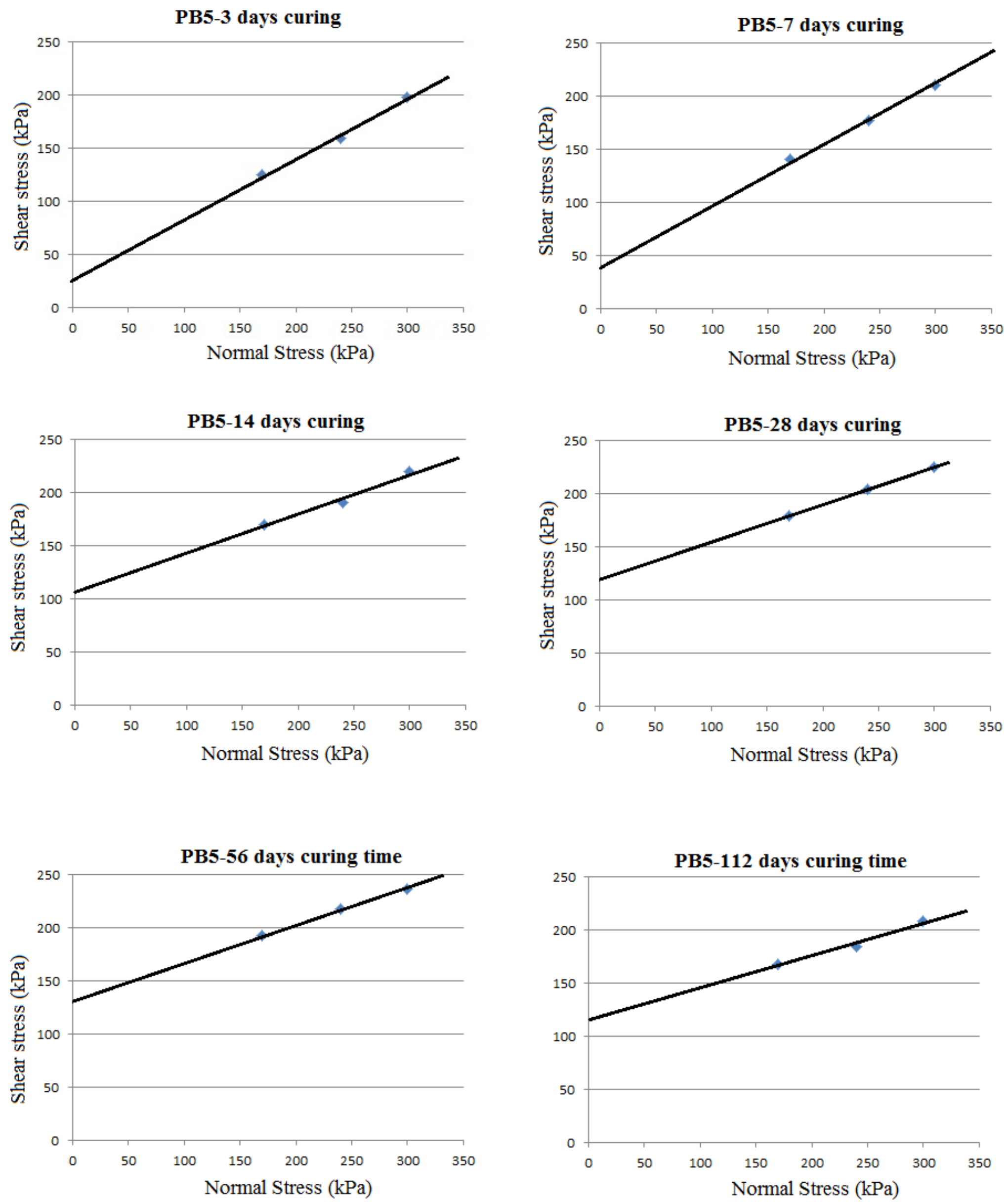

Figure 7. Some examples for shear strength variations under different normal stress conditions

Table 9. Cohesion value intervals calculated for the typical *n* values from 1.8 to 2.6

UCS (kPa)	200	400	600	800	1000	1200	1400
c (kPa)	25-36	50-72	75-108	100-144	125-180	150-216	175-252

Mixes with silt dominant particle size distribution, ~77% solid (cement+tailings) content including 5-7% cement in solid and ~23% water content by weight, which were tested in this study are typical CPB materials [28-36]. As 25^{o} was found to be a practically acceptable value of internal friction angle for CPB materials having no longer curing time than the period for start of the sulphate attack, cohesion values of CPB materials can be estimated using Equation 3 for different UCS values. In Table 9, cohesion values calculated for the *n* values from 1.8 to 2.6 are given as a rough suggestion for cohesion estimations from UCS values of typical CPB materials with pyritic tailings, as used in this study. Since various factors like cement type, tailings minerology, particle size distribution etc. can change the physico-mechanical properties of paste backfill materials, further studies are suggested for the assessment of different "*n*" values and usability of Table 9 for different CPB mixes.

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