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Research paper

The effect of particle size on the mechanical properties of Alkali Activated Steel Slag Mortar

Doh Shu Ing[1], Chia Min Ho[2], Li Xiaofeng[3], Ramadhansyah Putra Jaya[4], Mohd Mustafa Al Bakri Abdullah[5], Siew Choo Chin[6], Nur Liza Rahim[7], Marcin Nabiałek[8]

Abstract: With the rapid development of industry, abundant industrial waste has resulted in escalating environmental issue. Steel slag is the by-product of steel-making and can be used as cementitious materials in construction. However, the low activity of steel slag limits its utilization. Much investigation has been conducted on steel slag, while only a fraction of the investigation focuses on the effect of steel slag particle size on the properties of mortar. The aim of this study is to investigate the effect of steel slag particle size as cement replacement on properties of steel slag mortar activated by sodium sulphate (Na_2SO_4). In this study, two types of steel slag, classified as fine steel slag (FSS) with particle sizes of 0.075mm and coarse steel slag (CSS) with particle sizes of 0.150 mm, were used for making alkali activated steel slag (AASS) mortar. Flow table test, compressive strength test, flexural strength test and UPV test were carried out by designing and producing AASS mortar cubes of (50 × 50 × 50) mm at 0, 10%, 20% and 30% replacement ratio and at 0.85% addition of Na_2SO_4. The results show that the AASS mortar with FSS possess a relatively good strength in AASS mortar. AASS mortar with FSS which is relatively finer shows a higher compressive strength than CSS up to 38.0% with replacement

[1]PhD., College of Engineering, University Malaysia Pahang, 26300 Gambang Kuantan Pahang, Malaysia, e-mail: dohsi@ump.edu.my, ORCID: 0000-0001-6607-0552
[2]MSc., College of Engineering, University Malaysia Pahang, 26300 Gambang Kuantan Pahang, Malaysia, e-mail: hochiaminn@gmail.com, ORCID: 0000-0003-2099-3049
[3]PhD, College of Engineering, University Malaysia Pahang, 26300 Gambang Kuantan Pahang, Malaysia, e-mail: mr.leexiaofeng2018@gmail.com, ORCID: 0000-0003-3289-0717
[4]Prof., College of Engineering, University Malaysia Pahang, 26300 Gambang Kuantan Pahang, Malaysia, e-mail: ramadhansyah@ump.edu.my, ORCID: 0000-0002-5255-9856
[5]Prof., Faculty of Chemical Engineering Technology, University Malaysia Perlis, Malaysia, e-mail: mustafa_albakri@unimap.edu.my, ORCID: 0000-0002-9779-8586
[6]Prof., College of Engineering, University Malaysia Pahang, 26300 Gambang Kuantan Pahang, Malaysia, e-mail: scchin@ump.edu.my, ORCID: 0000-0001-5596-709X
[7]PhD., Faculty of Chemical Engineering Technology, University Malaysia Perlis, Malaysia, e-mail: nurliza@unimap.edu.my, ORCID: 0000-0001-6609-8512
[8]Prof., Department of Physics, Częstochowa University of Technology, Poland, e-mail: nmarcell@wp.pl, ORCID: 0000-0001-6585-3918

ratio from 10% to 30%. This study provided the further investigation on the combined influence of replacement ratio and particle size of SS in the properties of fresh and hardened AASS.

Keywords: compressive strength, flexural strength, particle size, sodium sulphate, steel slag

1. Introduction

Stee slag (SS) is a solid waste from the steel-making industry which is generated in the process of smelting. Normally, SS is classified based on the type of the smelting furnace namely basic oxygen furnace, electric arc furnace and ladle furnace, correspondingly generate basic oxygen furnace slag, electric arc furnace slag and ladle furnace slag [1]. The generation of one ton of crude steel leads to approximately 150–200 kg of steel slag [2]. According to the World Steel Association, there was approximately 1808.6 million tons of crude steel product were produced in 2018, with approximately 250 million tons of steel slag [3]. Such a large amount of SS is normally piled up in the landfill while causing environmental pollution [2, 4, 5]. Therefore, many countries attempt to reduce the accumulation of SS in the way of re-utilizing SS.

Previous studies showed that the particle size of SS has influence on the properties of fresh and hardened concrete [6–10]. Some studies focus on smaller SS particle size which is finer than 100 µm. The increase of SS fineness is regarded as an effective method to improve the reactivity of SS. In the study of [11], SSs with different particle sizes less than 80 µm were used to replace cement up to 30%. It is observed that the particle size of SS influences the compressive strength of concrete significantly. The concrete with particle size 45–80 µm showed the optimum 28 days compressive strength at 5% cement replacement ratio. However, when the replacement ratio exceeded 5%, the particle size 0–15 µm showed optimum 28 days compressive strength at every cement replacement ratio. Wang et. al [12] studied two different particle size namely less than 20 µm and more than 20 µm. Negligible influences were traced on the compressive strength, drying shrinkage and permeability of concrete at 28-day curing age when replacing cement by fine SS within 20%.

The addition of activator is another method to improve the activity of SS concrete. Sodium silicate, sodium hydroxide and sodium carbonate are the common activators used to activate fly ash, ground granular blast furnace slag, SS, etc [13–17]. The mechanical properties, durability and microstructural characteristics of concrete activated by various activators were closely investigated in these studies. In the study of [18], the compressive strength of cement-slag binder pastes samples activated with sodium silicate and sodium sulphate showed increment at 28-day curing age compared to the control samples. The addition of activator promotes the dissolution of SS leading to the formation of more hydration products.

Hence, the objective of this study is to investigate the effect of SS particle size on the mechanical properties of SS mortar. Two types of SS, namely fine SS (< 75 µm) and coarse SS (< 150 µm), are used to replace cement in producing SS mortar. Flow table test, compressive strength test, flexural strength tests and UPV test were carried out to investigate the effects of particle size on the mechanical properties of SS mortar.

2. Materials and methodology

2.1. Raw materials

This study used Portland limestone cement with the strength grade 32.5 which conformed to MS EN 197-1:2014 CEM II/B-L 32.5N standards. The steel slag used was basic oxygen furnace steel slag. Table 1 shows the chemical composition of cement and steel slag. The steel slag was divided into two types namely fine steel slag (FSS) with < 75 µm particle size and coarse steel slag (CSS) with < 150 µm particle size. The particle size distribution of FSS and CSS is shown in Fig. 1. The specific surface area of cement, CSS and FSS are 359 m^2/kg, 405 m^2/kg and 478 m^2/kg, respectively.

Table 1. Chemical Composition of basic oxygen furnace steel slag

Oxide Group	Cement (%)	SS (%)
CaO	60.78	41.40
SiO_2	17.82	13.50
Al_2O_3	3.29	1.80
Fe_2O_3	2.55	19.70
MnO	–	5.33
SO_3	2.52	0.218
MgO	1.61	3.85
P_2O_5	–	2.55

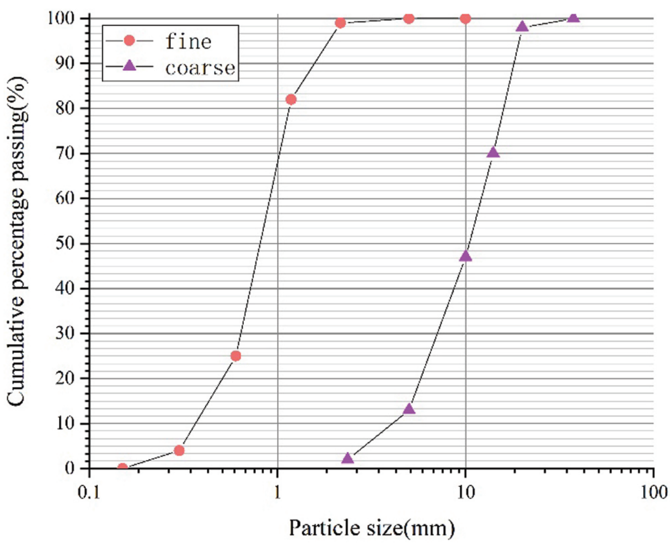

Fig. 1. Particle size distribution of FSS and CSS

The sand used in this study was natural river sand. The sand was dried and sieved using a mechanical shaker and the grading of sand is determined. The maximum size of sand is 2.36 mm. The sieve analysis of sand was determined by BS 812: Part 103. The cumulative passing sieve of sand through 0.15 mm, 0.3 mm, 0.425 mm, 0.6 mm, 1.18 mm, and 2.36 mm are 4.92%, 11.94%, 29.56%, 58.62%, and 100%, respectively. The percentage of cement, water and sand used in this study was 1:0.6:3, by mass, according to JGJ/T70 [19]. Sodium Sulphate (Na_2SO_4) was used as chemical activator to improve the properties of mortar. The percentage of Na_2SO_4 used was 0.85% of water mass.

2.2. Test method

Mortar mixture was prepared for the determination of flow table value for its workability. two different particle sizes of steel slag as cement replacement in mortar were prepared with replacement ratios of 10%, 20% and 30%. the water-binder ratio of the mixture is 0.60 and the cement-sand ratio is 1:2.75. The flow table value was measured for the fresh mortar mixture after achieving a homogenous mix. All the mixtures were cast into plastic cubes after mixing and then cured at the ages of 1-day, 7-day and 28-day with temperature 24 ± 5°C.

In order to study the compressive strength of steel slag cement mixture, cube samples of size (50 × 50 × 50) mm were prepared. the samples were cured at room temperature 24 ± 5°C in water. at the curing age of 1-day, 7-day and 28-day, the compressive strength of the cement mortars were tested under bs en 1015-11:1999 [20]. Meanwhile, ultrasonic pulse velocity test was carried out according to bs 1881: Part 203:1986 at 28 days of curing age [21].

Mix proportions of all mortar samples are summarized in Table 2. Sample C0 is the pure cement mortar as control specimen. samples C10, C20, C30 were 10%, 20% and 30% (by mass) of cement replacement with coarse steel slag, respectively. meanwhile, samples CF10, CF20 and CF30 were 10%, 20% and 30% (by mass) of cement replacement by fine steel slag, respectively.

Table 2. Mix Proportion of cement mortar at W/B of 0.6/ (kg/m^3)

Samples	Sand	Cement	Steel Slag	Water	Na_2SO_4 (%)
C0	4125	1500	0	900	0.85
C10	4125	1350	150	900	0.85
C20	4125	1200	300	900	0.85
C30	4125	1050	450	900	0.85
CF10	4125	1350	150	900	0.85
CF20	4125	1200	300	900	0.85
CF30	4125	1050	450	900	0.85

3. Results and discussion

3.1. Workability

Figure 2 shows the flow table value of the fresh mortar with the addition of steel slag with two types of particles size. the flow table value of fresh mortar increased with the increasing ss replacement ratio from 0% to 20% and then decreased when ss replacement ratio was above 20% in both particles size of steel slag. this can be attributed to that more water was absorbed by ss when ss replacement ratio increase because of the relatively rough texture of ss [22]. It is believed that the specific surface area of steel slag with rough surface increased when the steel slag content increased. meanwhile, there are more voids between the steel slag particles or between the steel slag particles and cement particles because of their irregular shape, which results in the demand of more water to maintain the desired slump [11, 21]. it was also observed that fresh mortar with fss has a lower flow value compared to css at the same replacement ratio, which can be attributed to the higher specific surface area of fss than that of css. more water is absorbed by the surface of fss with the higher specific surface area, hence, the flow value of fresh mortar with fss decrease [11]. the result of flow table ranges from 200–215 mm complies with bs en 1015-3: determination of consistence of fresh mortar (by flow table test) which allows the flow of 210 ± 5 mm with 25 falls drops in 15 s [23].

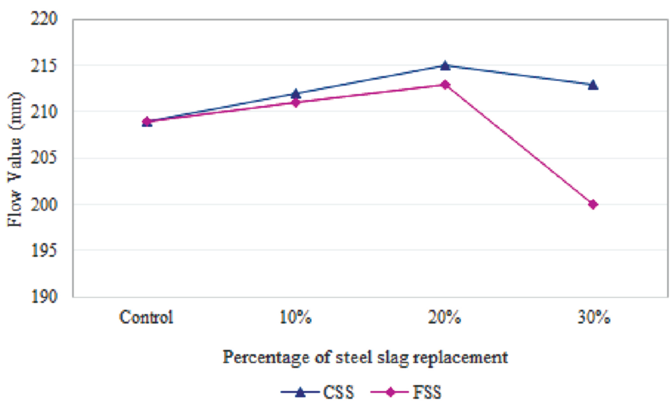

Fig. 2. Flow table value of fresh mortar

3.2. Compressive strength

Figure 3 shows the influence of steel slag with different particles size on the compressive strength with replacement ratio of 0%, 10%, 20% and 30% at 1-day, 7-day and 28-day curing age. It was observed that the replacement of cement by steel slag has an adverse effect on the compressive strength of mortar at all curing age. With the increase in replacement ratio of CSS from 0 to 30%, the compressive strength of mortar decreases from 5.99 MPa to 0.54 MPa, 13.54 MPa to 4.63 MPa and 15.81 MPa to 6.51 MPa at 1-day, 7-day and 28-day curing age, respectively, while for the replacement of cement by FSS, the compressive strength of mortar decreases from 5.99 MPa to 0.56 MPa, 13.54 MPa to 5.25 MPa and 15.81 MPa to 10.5 MPa at 1-day, 7-day and 28-day curing age, respectively. The compressive strength of mortar with steel slag has a lower strength than control at all curing age which can be attributed to the lower amount of calcium silicate hydrate (C–S–H) gels generated by steel slag compared with the equivalent cement because the steel slag has lower cementitious components and the exist of inert phase [12]. Mortar with FSS obtained a higher compressive strength than CSS mortar at the same replacement ratio. This is because that the fine steel slag mixture has a higher specific surface area than coarse steel slag which makes FSS mortar hydrates much faster compared to the CSS mortar [9]. Figure 4 shows the strength activity index of steel slag mortar at 1-day, 7-day

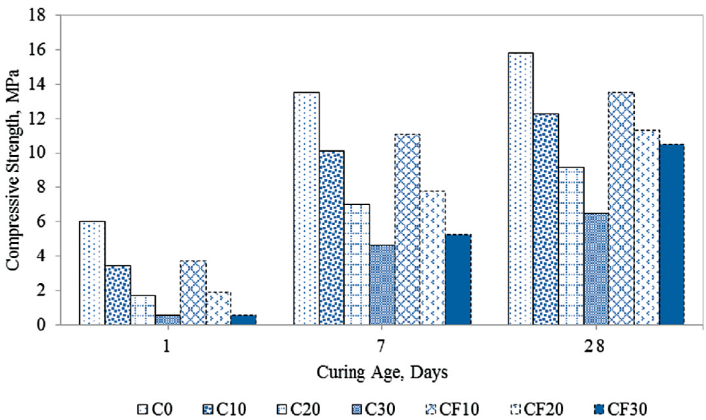

Fig. 3. Compressive strength of the mortars at different curing age

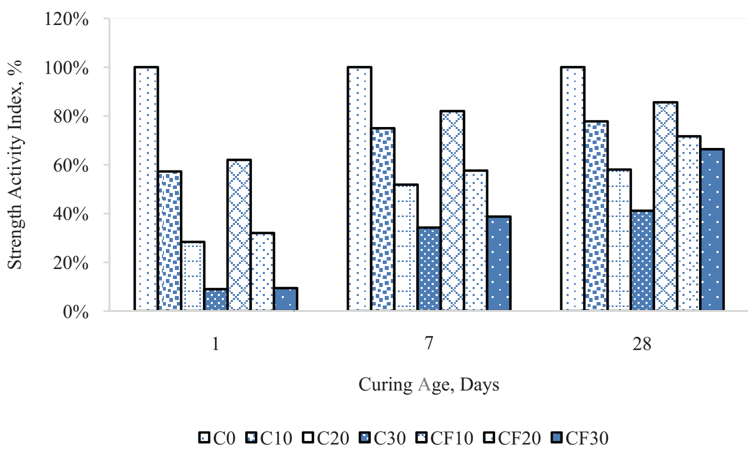

Fig. 4. Compressive strength index of steel slag mortar at different curing age

and 28-day curing age. It can be seen that all the mortar mixes showed the lowest strength index at 1-day compared with the strength index at 7-day and 28-day because steel slag has low reaction activity at early curing age [24]. The strength index of mortar increases with the increase in curing age. It is notable that the strength of mortar is comparable to control specimens when steel slag replacement ratio at a low level. At 10% of steel slag replacement ratio, the strength index of mortar is 78% and 86% for FSS mortar and CSS mortar, respectively, at 28-day curing age. A similar result is confirmed by Liu et al. [25]. Besides, the strength index of CSS mortar is lower than that of FSS mortar at the parallel replacement ratio.

3.3. Flexural strength

Flexural strength of mortar with and without replacement of steel slag is shown in Fig 5. Normally, the flexural strength of mortar or concrete specimens have similar trend with compressive strength [26], which can also be observed in this study. With the increase in replacement ratio of CSS from 0 to 30%, the flexural strength of mortar decreases from 1.39 MPa to 0 MPa, 2.16 MPa to 0.64 MPa and 2.98 MPa to 1.07 MPa at 1-day, 7-day and 28-day curing age, respectively, while for the replacement of cement by FSS, the compressive strength of mortar decreases from 1.39 MPa to 0 MPa, 2.16 MPa to 0.8 MPa and 2.98 MPa to 1.32 MPa at 1-day, 7-day and 28-day curing age, respectively. The flexural strength of FSS mortar were slightly higher than that of CSS mortar ranging from 0.09 MPa to 0.19 MPa, 0.15 MPa to 0.2 MPa and 0 to 0.25 MPa at the parallel replacement ratio of 10%, 20% and 30%, respectively. It is notable that the flexural strength of mortar with steel slag replacement ratio of 30% have no strength at 1-day curing age which may due to the type of cement used cannot generate enough C-S-H gel at 1-day curing age to provide early strength.

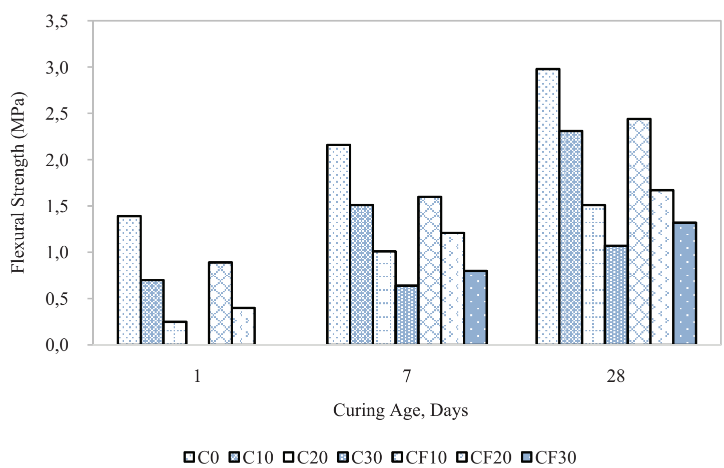

Fig. 5. Flexural strength of the mortars at different curing age

3.4. Ultrasonic pulse velocity

Figure 6 shows a significant decrease in trend of ultrasonic pulse velocity (UPV) for FSS and CSS cement mortar at 28 days of curing age. The UPV value of CSS cement mortar at three replacement ratios decreased by 4.48%, 8.70% and 14.01% compared to the control specimen of 2842.17 m/s and decreased by 1.79%, 2.79% and 4.17% for FSS cement mortar. The decrease in UPV value of mortar with the increase in steel slag replacement ratio may be due to the shape of steel slag. The irregular shape of steel slag can cause void between the steel slag particles or between the steel slag and the cement particles [11,25]. As shown in Figure 6, the UPV value for FSS cement mortar has a higher velocity than CSS cement mortar of 76 m/s, 168 m/s and 280 m/s at steel slag replacement ratio of 10%, 20% and 30%, respectively. This is due to the filling effect of FSS in mortar and reduce the void in mortar compared to CSS mortar. It is believed that the steel slag particle with smaller size has higher specific surface area and are able to occupy the mortar voids efficiently. Hence, the UPV value increased when steel slag particles are finer [28]. Moreover, the surface of steel slag is considered rough and porous, thus, the void between the mortars is larger than the control specimen [7]. It finally causes the velocity to decrease compared to the control specimen. Similar result has been observed in the study of [29], in which UPV of steel slag concrete increased with the increase in steel slag replacement.

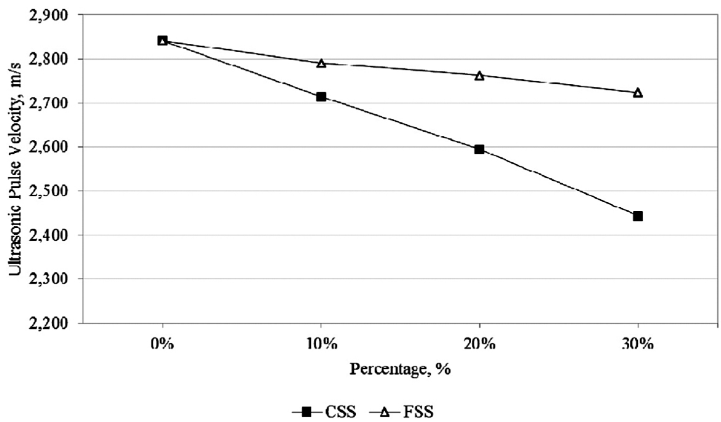

Fig. 6. Ultrasonic pulse velocity for different mortar types at 28 days

3.5. Correlation between compressive strength and ultrasonic pulse velocity

Figure 7 shows the correlation between compressive strength and ultra-pulse velocity (UPV). It is observed that the determination coefficient (R^2) for CSS and FSS cement mortar are 0.9891 and 0.9651, respectively. The higher value of R^2 indicates the better correlation between compressive strength and UPV. The correlation between compressive strength and UPV is obtained from Equation 3.1 and 3.2. Symbol X and Y represent the value of UPV and compressive strength of cement mortar in MPa, respectively. This indicates that compressive strength has a strong relationship with ultrasonic pulse velocity. A similar outcome was reported by Mahure et al. [30].

$$\hat{y} = 0.02349X - 51.27296 \tag{3.1}$$

$$\hat{y} = 0.04696X - 117.76253 \tag{3.2}$$

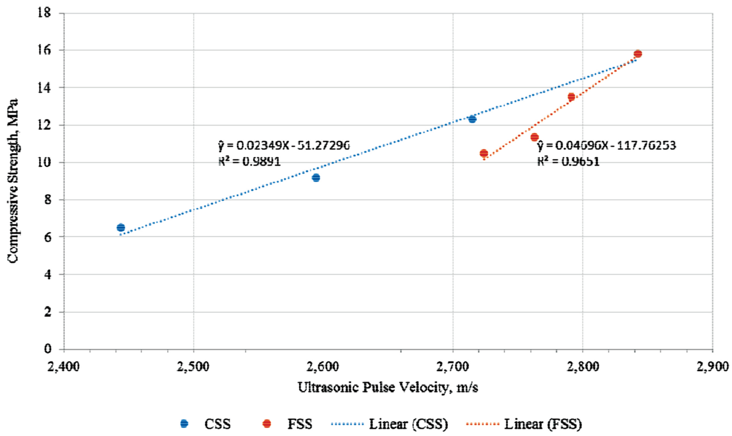

Fig. 7. Correlation between compressive strength and ultrasonic pulse velocity of cement mortar with 0%–30% of CSS and FSS at 28 days

4. Conclusions

1. The flow table value of C0, C10, C20, C30, CF10 and CF20 had fulfilled the standard of 110±5% which is 109%, 112%, 115%, 113%, 111% and 113%, respectively. Findings showed that for both particle sizes of steel slag as cement replacement in mortar mix could increase the flow table value and thus producing mortar with better workability.
2. The partial cement replacement of steel slag with both particle sizes decreased the compressive strength of cement mortar. The highest compressive strength for 28 days for CSS cement mortar achieved was C10 of 12.30MPa while for FSS cement mortar was CF10 of 13.53MPa. The strength achieved for both particle sizes were 77.80% and 85.58% of to the control specimen.
3. FSS cement mortar obtained a higher compressive strength compared to CSS cement mortar in the range from 9.09% to 38.0% of replacement ratio from 10% to 30% at 28 days.
4. The flexural strength of mortar with and without steel slag showed similar trend with the compressive strength.

5. In terms of UPV, FSS with smaller particles size managed to fill the voids efficiently as compared to CSS. Thus, the UPV value for FSS is relatively higher since the specimens are more compact and dense.
6. The optimal cement replacement ratio for both particle sizes of steel slag were at 10%. The addition of steel slag exceeding 10% replacement ration reduces the compressive strength of the cement mortar.

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