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ORIGINAL RESEARCH PAPER

Long-term and microstructural studies of soft clay stabilization using municipal solid waste and Nano-MgO as an Eco-Friendly Method

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ABSTRACT

This study provides a practical solution to manage non-hazardous waste and aid the environment. The largest group of non-hazardous waste is called municipal solid waste (MSW) which can be effectively used as an alternative material in civil projects. In this research, as an alternative to traditional modification methods of soil which causes global warming, the soft clay (Clay) was chemically modified by four different percentages of MSW in soil dimensions (15%, 25%, 35%, 45%) in 28 and 120 days. The optimum percentage of MSW addition (15%) to the Clay at the curing age of 28 days increased the unconfined compressive strength (UCS) and California bearing ratio (CBR) by 1.28 and 3.34 times, respectively. Given that higher percentages of MSW reduce the UCS and CBR in the specimens, four percentages of Nano-MgO, i.e., 0.25, 0.5, 0.75, and 1% were used for stabilization. The specimens containing optimum percentages of MSW (15%, 25%) and stabilized with 1% Nano-MgO could improve UCS and CBR 2.34 and 5.59 times, respectively that results had better durability over 120-days which can be attributed to the CBR testing condition. The cause of the increase in UCS and CBR was investigated using microstructural analysis for 120 days of curing. The specimen with high durability approved the cement bond formation with Anorthite & Dolomite minerals. In conclusion, using optimum MSW and Nano-MgO effectively solved the Clay problems in suitable conditions and allowed higher percentages of MSW to be removed from the environment.

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1. Background

Protecting human health and the environment in a world rapidly becoming more and more complicated is considered a major challenge for the international community (Fataei et al., 2017; Farsani et al., 2022). In the previous decades, the application of inappropriate approaches for the management of generated waste materials disposal has caused serious human health problems and environmental concerns in the world (Masoumi and Jalilzadeh, 2020; Heidari Farsani et al., 2021). Therefore, in recent years, the minimization of urban waste materials and their reuse with environmentally friendly methods has been developed (Hemmati et al., 2019; Maleki et al., 2022). For ex. in the field of soil modification and stabilization as a new additive.

For more explanation, a traditional method of soil modification is the removal of soil and substitution with high-quality materials (Ghobadi et al., 2014). Due to a lack of access to suitable alternative soil and the high costs of transfer, Researchers are looking for alternative approaches (Salimi and Ghorbani, 2020; Sameenezhad and Fataei, 2015, Aprila et al., 2023). Recent studies have introduced soil stabilization as one of the most cost-effective and simplest approaches to improving the behavior of soil (Ghorbani et al., 2019; Vakili et al., 2018; Mola-Abasi et al., 2018). Chemical stabilization by adding cementitious materials to the soil, such as cement, lime, and gypsum enhances soil properties (Consoli et al., 2019; Consoli et al., 2018; Saadat and Bayat, 2022; Salehi et al., 2021). However, the mentioned traditional stabilizers have unavoidable environmental consequences due to emitting a large volume of greenhouse gases into the atmosphere (Ghalambaz et al., 2021; Khajeh et al., 2020; Afrasiabian et al., 2021; Phummiphan et al., 2018), so in recent years replacing them with Eco-friendly alternatives has become common (Salimi and Ghorbani, 2020; Jalilzadeh et al., 2014). An example of such an option is Industrial waste (Sekhar and Nayak, 2018; Ge et al., 2018; Bilondi et al., 2018; Nasiri et al., 2021) that can reduce greenhouse gas emissions such as CO2 by remarkably limiting the use of traditional additives (Mohammadinia et al., 2018; Phummiphan et al., 2018; Bagheri et al., 2016; Cheng et al., 2021, Gholamin and Khayatnezhad, 2011). In trying to reduce CO2 emissions in the environment, another challenge is methane emissions, which are caused by improper disposal of municipal solid waste (MSW), which is a serious role in global warming (Arunthathi et al., 2022). MSW is non-hazardous waste that growing in tandem with population growth, which is generated by our daily activities (Kazemi et al., 2016). Converting this vast amount of MSW into new materials and energy is a reasonable approach to reduce reliance on scarce natural resources while promoting a more circular and climate-neutral economy (European Commission, 2020). As a result, identifying the effective use of MSW in secondary works or as an alternative in civil engineering is now necessary (Arunthathi et al., 2022; Parvaneh, 2021; Hosseinzadeh and Parvaneh, 2020).

In Iran, MSW management is weak, therefore, utilizing and extracting MSW provides an excellent chance for environment management in Iran. On the other hand, in Southern Iran, road construction projects have encountered soft clay (Clay). Stabilization of such soil with traditional methods is not Eco-friendly. Thus, it is critical to stabilize Clay with non-hazardous MSW that has a serious role in global warming and pollutes the environment. Accordingly, the current research proposes a sustainable innovation by using these materials in Clay stabilization. The Clay stabilized with MSW, and Nano-MgO was also subjected to UCS and CBR tests over curing periods of 28 and 120(Hadavand Khani et al.,2017). From a microstructural perspective, X-ray diffraction (XRD), field emission scanning electron microscopy (FE-SEM), and energy dispersive spectrometry (EDS) were performed to evaluate the interactions between the Clay, MSW, and Nano-MgO and gain an understanding of reaction mechanisms. The findings of this study advocate using MSW and Nano-MgO as alternative additives for road construction base materials that require mechanical characteristics improvement.

2. Materials and Methods

1.2. Materials

The studied soil in this research was chosen from the south of Iran (Shiraz). The grain size distribution curve of this soil shows in Fig. 1 according to (ASTM D422). Standard compaction (ASTM D698), Atterberg limits (ASTM D4318), UCS (ASTM D2166), CBR (ASTM D1883), XRD (BS-EN 13925-2), and XRF (ASTM E 16211(2013) are summarized in Table 1. Given that, 92% of this soil passed through sieve No. 200, based on its plasticity index (PI), classified as CH. The UCS and CBR of the investigated clay (CH) are 0.48 N/mm^2 and 2.96%, respectively. Based on the CBR value, the clay was classified as poor to fair (Mina et al., 2019). Based on the result of XRD analysis, 53.4% calcium carbonate content was in the clay. Thus, this soil was defined as Caly.

In addition to the Clay, the Nano-MgO, and MSW additives were used. The MSW was collected from the south of Iran (Shiraz). In this area, 800 tons of MSW are produced daily, with only 3% separated and the rest disposed of. The U.S. Environmental Protection Agency (EPA) recommends various processes for MSW management (EPA, 2013). Hence, in the current study, the MSW, which included daily non-hazardous waste, was collected from rubbish collection bins and aerated. The aerated MSW was ground and filtered through sieve 5 (4mm) and the waste passed through sieve No. 5 was packed as compost. The remaining materials on sieve No. 5 which cannot be used, are rejected and are usually deposited in landfills but this part of the MSW is the main purpose of this research which has been used for soil improvement before entering the landfill. Fig.

2(a,b) compares the normal algorithm of waste recycling factories and the modified algorithm in this article. The difference between the two forms is in removing the landfill from nature. Because the rejected MSW did not have a specific nature, no microstructural or chemical tests were required.

Furthermore, Nano-MgO was added to Clay containing MSW with properties that were determined by the method suggested by Vijayan and Jose (2022). Adding Nano-MgO to the soil was reported to reduce its plasticity index, plasticity limit, liquid limit, and shrinkage limit (Harsh et al., 2022; Majeed and Taha, 2012) while increasing its UCS and CBR (Harsh et al., 2022).

Table 1. Some geo-environmental and geotechnical properties of the Clay

Geo-environmental and geotechnical Properties	Measured quantity
XRD Analysis	Calcite (53.4%), Quartz (10.8%), Illite (15.2%), Chlorite (6.7%), Albite (7.8%), Orthoclase (6.1%)
XRF Analysis	Na2O (0.4%), SO3 (<0.01%), Fe2O3 (4.8%), MgO (4.5%), Cl (<0.01%), TiO2(0.5%), Al2O3(9.1%), K2O (1%), L.O.I(18.8%), SiO2(43.9%), CaO (17%), La&Lu (<0.01%), P2O5(<0.01%)
Liquid limit (%)	69.94
Plastic limit (%)	28.23
Plasticity index (%)	41.71
Optimum moisture content (%)	25
Maximum dry density (Kn/m3)	14.70
Unconfined Compression Strenght (UCS) (N/mm2)	0.48
California Bearing Ratio (CBR) (%)	2.96
Classification	CH

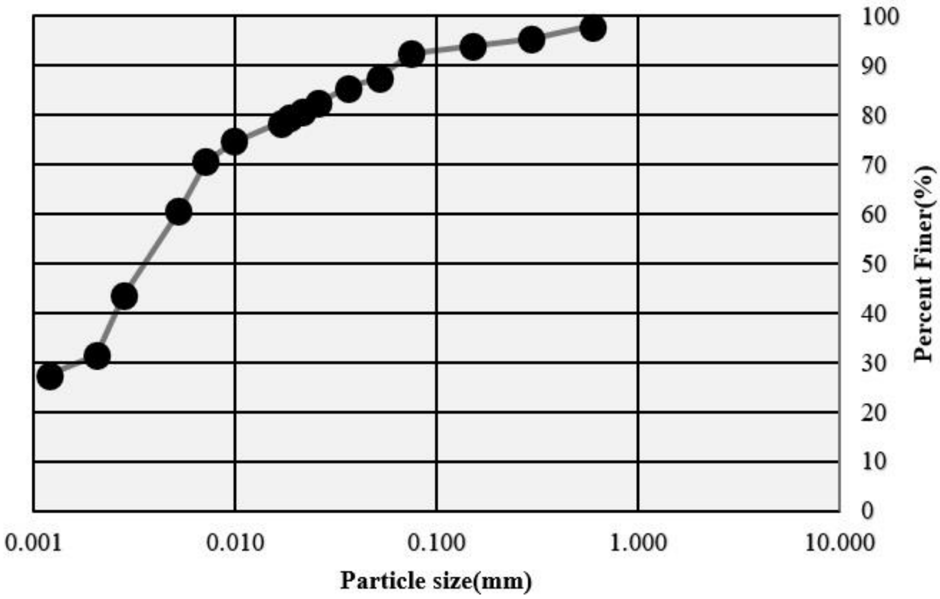


Fig 1. Particle size distribution curves of the studied Clay

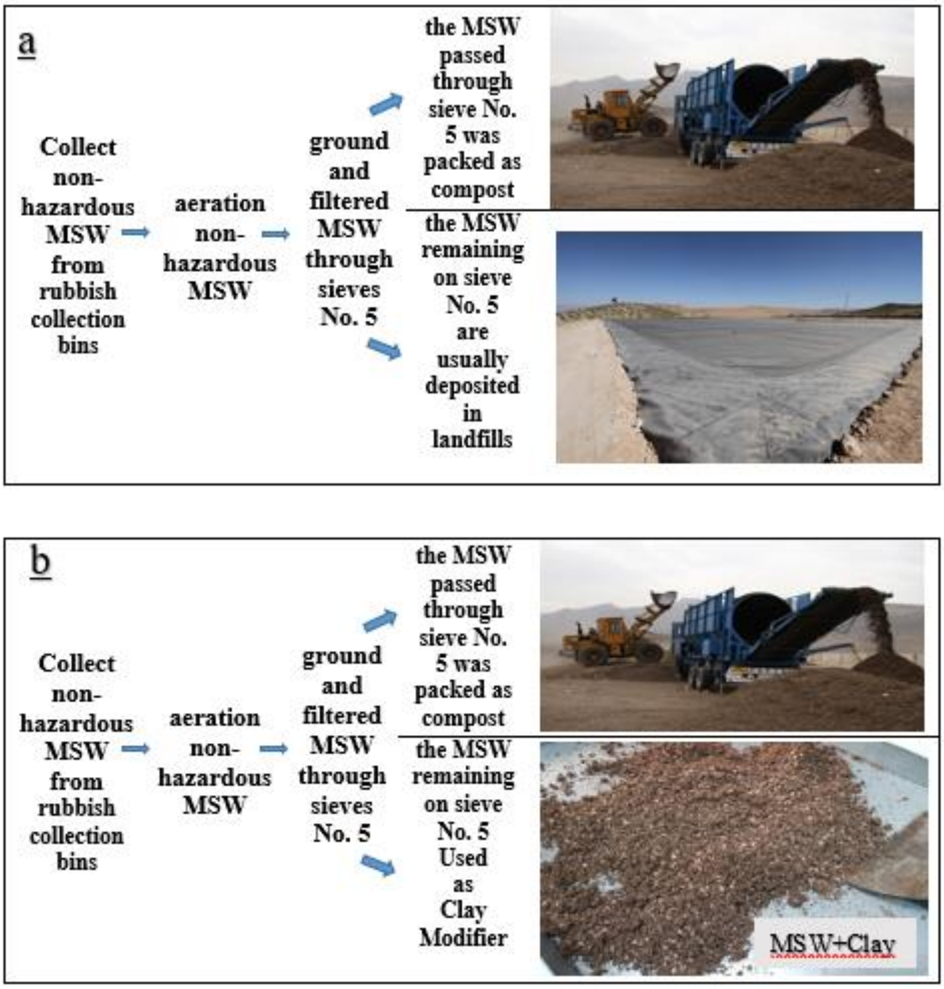


Fig 2. (a: Normal algorithm of waste recycling factory; b: The modified algorithm in this study to use rejected MSW)

2.2. Mix Designs

The strength behavior of mixed Clay with different percentages of MSW (15, 25, 35, and 45%) was investigated first. Numerous studies have shown that a small amount of nanomaterials can significantly affect the chemical and physical properties of the soil (Vijayan and Jose, 2022). According to the economic point of view, 0.25, 0.5, 0.75, and 1% of soil weight, Nano-MgO were added to stabilize the Clay mixed with MSW.

First of all, the Clay and MSW were passed through sieve No. 4 (4.75mm), separately. Then based on the compaction characteristics (OMC and MDD) (Buritatum et al., 2022), the water fractions and the MSW fractions were added to Clay and mixed well, and MSW-modified specimens is made. Then MSW-modified specimens stabilized with various percentages of Nano-MgO. Accordingly, the water-Nano-MgO suspension, using a magnetic mixer, was mixed continuously to prevent the nanomaterials from settling while being added to maintain homogeneous dispersions (Ge et al., 2022).

All mixtures were kept in sealed plastic bags in the laboratory for 24 hours for cation exchange (CE) and moisture preservation. Then the moist homogeneous for UCS test, mixtures were placed in cylindrical steel molds with heights and diameters of 140 mm and 70 mm, respectively, next they were placed under static compaction to obtain the maximum dry density and re-molded the specimens (Bakhshizadeh et al., 2022), and for the CBR test, they were subjected to dynamic compression in a special mold. For 28 days of curing, re-molded specimens were kept in sealed plastic bags in the laboratory for moisture preservation. According to the testing program described, the specimens were made for both UCS and CBR tests. Finally, among the re-molded specimens with 28 days of curing, specimens were selected for testing with longer curing (120 days).

3.2. Testing Program and Methods

UCS and CBR tests were performed to evaluate the mechanical properties of the specimens. The stabilized and modified specimens were subjected to UCS tests at a constant strain rate of 1.2 mm/min per (ASTM D2166). Following that, a series of CBR tests were performed according to (ASTM D1883) to evaluate the specimens' bearing capacity.

According to Eqs. 1, and 2 two non-dimensional parameters (UCSI and CBRI) were used for the two parameters UCS, and CBR to investigate the improvement in the stabilized and modified specimens. The values of UCS and CBR for each stabilized and modified specimen in the 28 and 120 days were divided by UCS and CBR of the non-stabilized and non-modified specimen. If the results of these divisions are more than one, there is an outcome about the additives' effectiveness in the stabilization and modification of Clay. Therefore, the optimum percentages of additives for stabilizing and modifying Clay can be better obtained. Finally, the microstructural analysis of the natural Clay and the stabilized specimens at the curing age of 28 days and temperature of 25°C was performed using EDS, XRD, and FE-SEM. The specimen images were magnified 10,000 times.

UCS Improvement (UCSI)=(UCS of stabilized samples)/(UCS of unstabilized samples) (1)

CBR Improvement (CBRI)=(CBR of stabilized samples)/(CBR of unstabilized samples) (2)

3. Results

1.3. Effect of MSW on the Clay

Fig. 3 demonstrates the effect of MSW on the UCSI and CBRI at the curing ages of 28 days. Based on the UCSI results, Clay+15%MSW had the highest UCSI (1.28), decreasing at a constant slope to Clay+45%MSW. Hence, Clay+15%MSW is expected to fill the Clay pores, flocculate the Clay structure, and increase density. However, at higher MSW content, the lower density of the MSW predominated over the main Clay structure, resulting in a dispersed structure with higher water absorption (Arunthathi et al., 2022), such that the bonding materials gradually reached a state where they could no longer sustain the compressive stress. The specimens' dispersed structure prevented the rise in UCSI (Clay+35%MSW) or reduced it (Clay+25%MSW, Clay+45%MSW) compared to specimen Clay.

From an environmental point of view, although specimen Clay+15%MSW had the highest UCSI, the authors recommend using Clay+35%MSW at 28-days to eliminate additional MSW for Clay modification since the UCSI difference between Clay+15%MSW and Clay+35%MSW at the period of 28-days was only 0.17, and Clay+35%MSW is expected to result in a higher UCSI at a longer curing age. Consequently, MSW can modify the Clay with a more significant percentage, allowing higher percentages of MSW to be removed from the environment.

Based on the CBR results, all 28 days specimens had a CBRI greater than one, with a maximum value of 3.43 (Clay+15%MSW) and a minimum value of 2.29 (Clay+45%MSW). This can be attributed to the CBR testing condition, in which the specimen remains confined inside the mold. This is very promising because any percentage of MSW can be used depending on the expected goal, and it is an essential step toward eliminating MSW in CBR testing.

2.3. Effect of Nano-MgO on the Clay Containing MSW

The specimens with optimum percentages of MSW improved the soil structure by filling the pores, forming a flocculated structure, and decreasing the permeability of the specimens. However, extensively high percentages of MSW resulted in more pores by creating a dispersed structure with high water absorption or through the chemical interaction of Clay-MSW. The authors then attempted to add a small percentage of nanomaterials to the Clay containing MSW, given their small size, ease of access to small spaces, and long-term activity (Harsh et al., 2022), which could fill probable pores or neutralize the negative electrical charge of the surfaces of the Clay-MSW particles, which is the main factor responsible for moisture absorption via the exchange of divalent cations of Nano-MgO.

Figs. 4(a, b, c, d) depict the UCSI and CBRI results of the specimens stabilized with Nano-MgO at 28 days of curing. Due to the rapid reactions of the nanomaterials, the UCSI of all specimens containing MSW increased with different slopes as the Nano-MgO percentage. However, when compared to the Clay, the UCSI did not increase in all specimens, such that in soil Clay+45%MSW+1%Nano-MgO (fig. 4d), almost no increase in UCSI was observed, indicating neither particle dispersion nor structural flocculation occurred. The positive effect of Nano-MgO appeared to be neutralized by the MSW, which could be due to microstructural results. By adding 1% Nano-MgO, UCSI= 2.34 was obtained in specimen Clay+15%MSW+1%Nano-MgO (Fig. 4a). This can prove that, in addition to the rise in the Clay density, other reactions resulted in better Clay stabilization. Another hypothesis is also possible. The goal of the Nanomaterial mix designs was to minimize nanomaterials accumulation while maximizing effectiveness. Mixing nanomaterials in the specimen with lower MSW yielded a better result, whereas the specimen with higher MSW produced no impressive result. A comparison of the results of Figs. 3 and 4 reveal that the optimum specimen Clay+15%MSW in Fig. 3 grew by 83% by adding 1% Nano-MgO, indicating that the addition of Nano-MgO aided in sustaining the load. However, specimen Clay+25%MSW+0.75%Nano-MgO with UCSI= 1.39 at the curing age of 28-days can make projects more cost-benefit and consume more MSW, compared to Clay+15%MSW and demonstrated better behavioral stability.

Based on the CBR results on the fig. 4(a, b, c, d), adding Nano-MgO to the MSW-containing specimens did not result in a rise in CBRI. These differences were noticeable in specimens with higher percentages of MSW. Nevertheless, all specimens had CBRI>1. The ideal specimen, according to the quantitative comparison, was specimen Clay+25%MSW+1%Nano-

MgO with CBRI=5.59. However, in order to have MSW removal, specimens Clay+35%MSW+0.25%Nano-MgO and Clay+35%MSW+0.75%Nano-MgO could grow by nearly 12% and 16%, respectively, compared to Clay+25%MSW. As a result, these specimens can be designated as optimum.

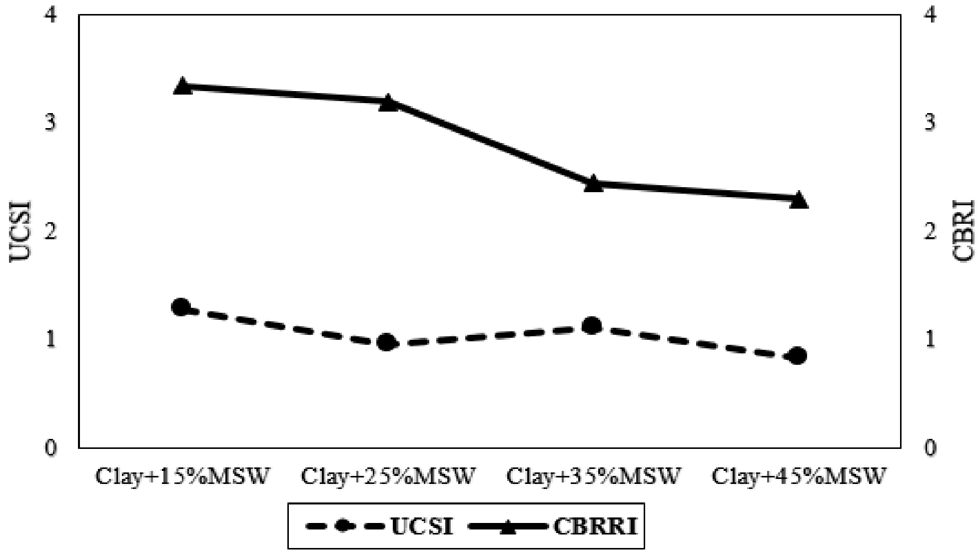


Fig 3. UCSI & CBRI of modified specimens with MSW at 28 days of Curing

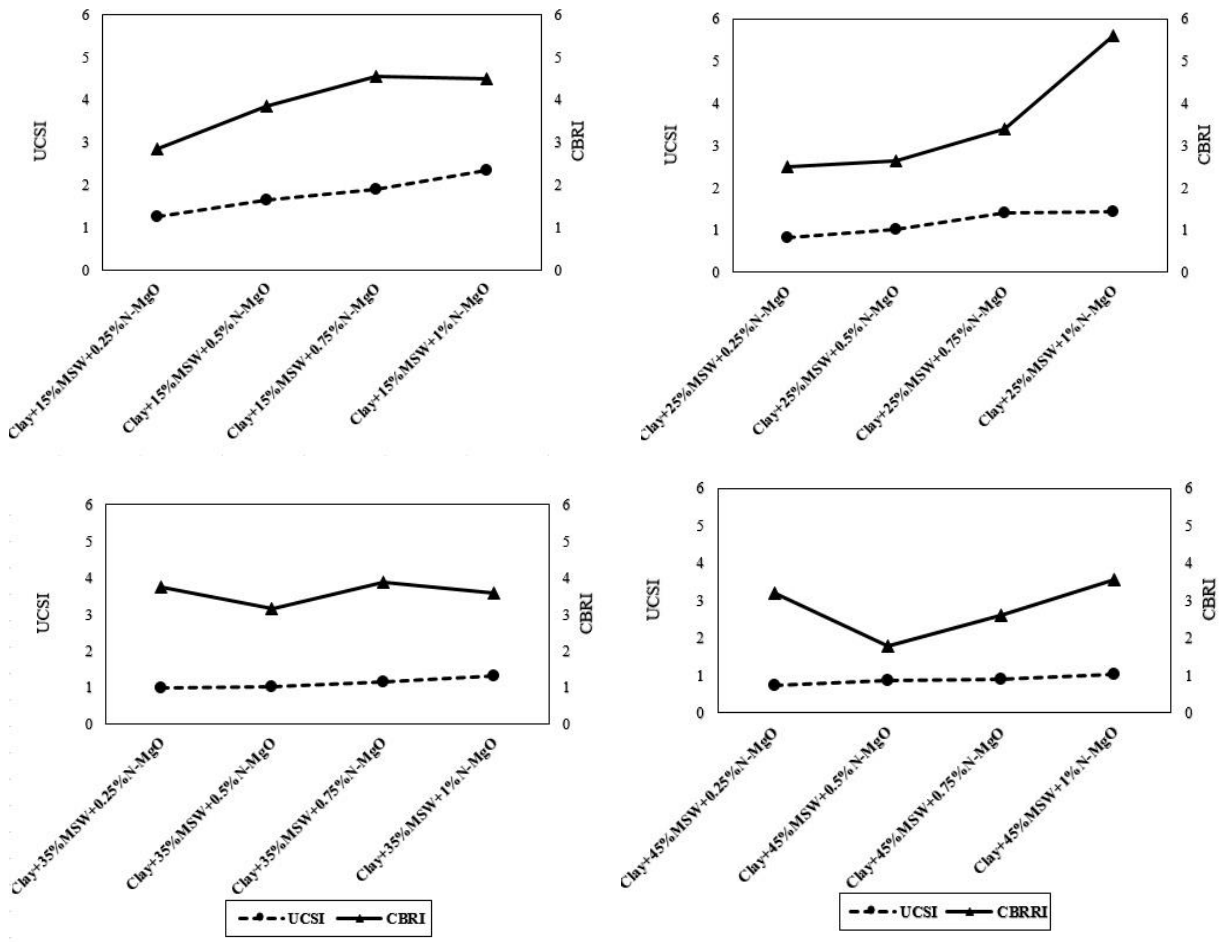


Fig 4. UCSI & CBRI of stabilized specimens with MSW & Nano-MgO at Curing= 28 days (a: Clay+15%MSW; b: Clay+25%MSW; c: Clay+35%MSW; d: Clay+45%MSW)

3.3. Effect of Long-Term Curing on Optimal Specimens

The specimens with optimum percentages of MSW and Nano-MgO were selected for 120 days of curing. These specimens included Clay+15%MSW from section 3.1 and Clay+15%MSW+1%Nano-MgO and Clay+25%MSW+1%Nano-MgO from 3.2 section that the comparison of their UCSI and CBRI is shown in Fig. 5a, b respectively. According to Figure 5a, the UCSI of all specimens decreased after 120 days. Clay+15%MSW+1%Nano-MgO with the highest UCSI at 28 days has decreased the most in 120 days and almost reached UCSI of Clay+25%MSW+1%Nano-MgO in 28 days.

On the other hand, it can be seen in Fig. 5b that the amount of reduction based on CBRI is less compared to UCSI, and only by 0.26 it has experienced lower bearing capacity improvement. This can be attributed to the CBR testing condition, in which the specimen remains confined inside the mold. This is very promising because Using MSW under the condition of high overhead and confining stress means removing MSW from the environment.

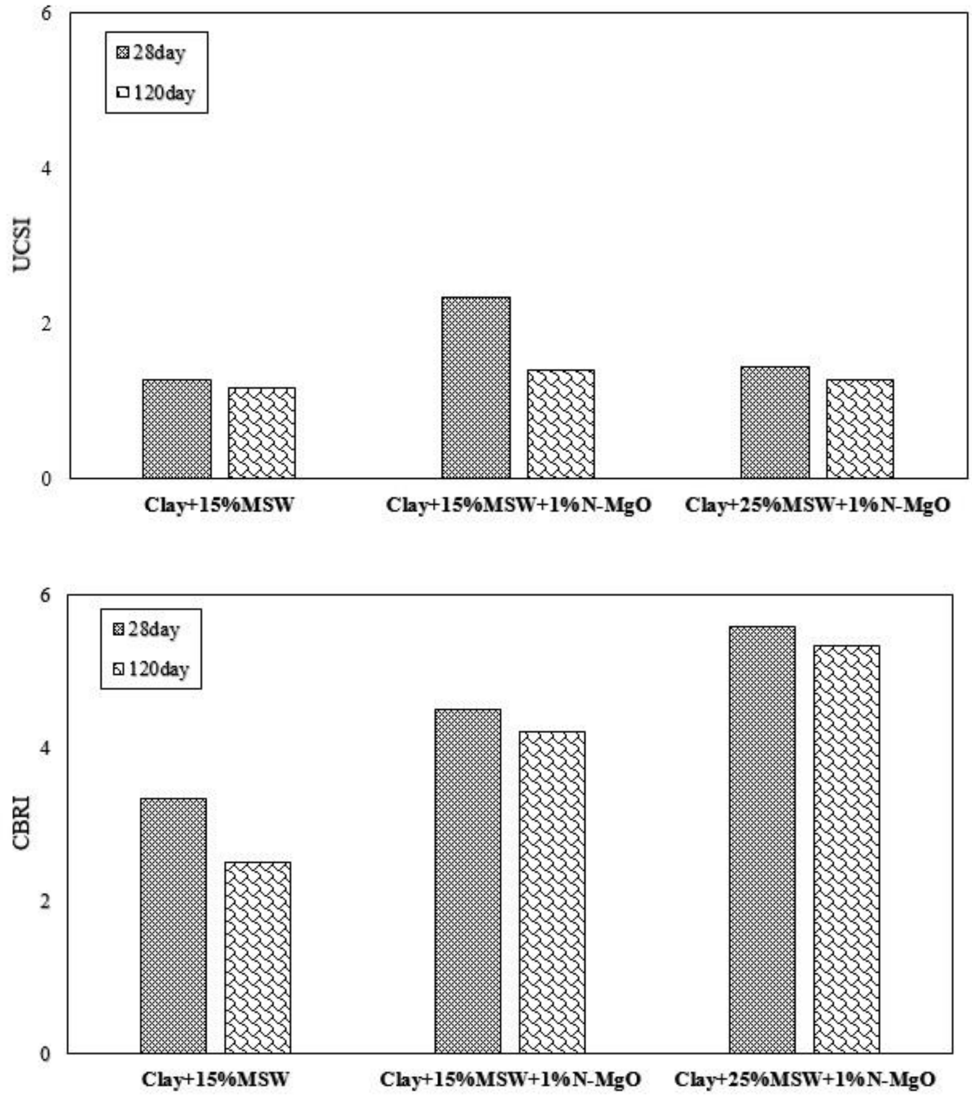


Fig 5. A comparison between UCSI & CBRI of optimum stabilized specimens at Curing= 28 & 120 days (a: UCSI; b: CBRI)

3.4. Microstructure

Because the microscopic interactions control the macroscopic soil deformation (Muntohar, n.d.), understanding changes in geotechnical properties, requires knowledge of the soil's chemical composition, mineralogical composition, and structural arrangement (Harsh et al., 2022), Thus, the FE-SEM, XRD, and EDS analyses were carried out on specimens Clay, Clay+15%MSW+1%Nano-MgO and Clay+25%MSW+1%Nano-MgO at the curing age of 120-days per relevant standard. These specimens were selected because they were optimum based on the UCS and CBR tests at 28 days but since Clay+15%MSW+1%Nano-MgO had the highest resistance drop in 120 days, it was an essential specimen for these analyses.

The primary factor determining soil's appearance, and physical, and chemical properties, such as compressive strength, is mineralogy (Ouhadi et al., 2006; Ajami and Fataei, 2015). Therefore, to gain a better understanding, the structure of Clay at the curing age of 120-days was first evaluated in Fig. 6. The Clay had calcite, quartz, illite, cristobalite, and kaolinite minerals in order from higher percentage to lower percentage. Calcite is a soluble carbonate mineral and the removal of this mineral significantly increases soil porosity and permeability (Wolfgang, 2004), so the microstructural analysis has also confirmed the need to modify and stabilize this type of soil.

In the following, the graphs related to the two stabilized specimens showed that the reflection of some minerals decreased and new reflections were observed, which indicates the effect of the additives. In such a way that in the specimen Clay+15%MSW+1%Nano-MgO, in addition to changing the peak intensity of the common minerals, the Cristobalite mineral at 2θ=20.03° has disappeared after adding the 15%MSW and 1%Nano-MgO. In contrast, the small peaks of Brucite, which were not visible in the XRD pattern at first, appeared at 2θ=18.77°, 39.82°, 48.87°, 56.20°). with the formation of Brucite, mechanical stress has been created in the soil structure, which has resulted in an unacceptable resistance from the UCS test (Greenwood & Earnshaw, 2012). The definitive result of this hypothesis can be examined more clearly through SEM.

About the specimen Clay+25%MSW+1%Nano-MgO, in addition to removing the Cristobalite mineral, Dolomite minerals were found at (2θ=31.22°, 68.46°) and Anorthite mineral at (2θ=12.76°, 28.21°, 35.04°). The presence of Dolomite as a double carbonate mineral containing calcium and magnesium and at the same time without water is a good sign. Dolomite has been able to precipitate, therefore, it has reduced the possibility of reducing the resistance, and with the buffer state it has created in the soil, it has prevented the changes in the pH of the soil and has stabilized the resistance behavior of the soil. On the other hand, the alteration of Calcite caused the formation of Anorthite in this specimen, and since Anorthite is rich in Ca-Al, it was able to help improve the resistance behavior of Clay by forming cement bonds (Handbook of Mineralogy), it can be concluded that the growth of Dolomite peaks And Anorthite is the main factor in improving soil resistance behavior. A more detailed investigation of this result is presented in SEM and EDS analysis.

In order to further identify the observed phases, SEM and EDS analysis have been performed because the new reflections observed in XRD, in addition to mineralogy changes, can be the reason for the production of new cement products. These results are shown in Figs. 7, 8, and 9. The result of SEM in Fig. 7 has shown that the Clay has a compact structure and many internal pores. In this fig, the apparent abundance of Calcite can be seen in a range from huge aggregates to all kinds of crystals. In this specimen, the ratio of Al/Si and Ca/Si is 0.36 and 0.65, respectively. As can be seen in Fig. 8 related to the specimen Clay+15%MSW+1%Nano-MgO despite the plate-shaped gels that indicate the formation of little cement bonds, there are still calcite minerals and voids. Considering the highest resistance drop in this specimen after 120 days, there is a possibility to confirm this hypothesis that the formation of Brucite has been able to create mechanical stress in the structure of the specimen. Therefore, the use of 15% MSW with 1% Nano-MgO after 120 days has been able to cause a magnesium attack and should be avoided. According to the EDS result of this specimen in Fig. 8, the amount of Al/Si has decreased slightly and Ca/Si has increased compared to Clay. The result of this reduction can be the formation of calcium aluminate hydrate (CAH), which appeared as sheet gels. But concerning the specimen Clay+25%MSW+1%Nano-MgO in Fig. 9, it is seen that by reducing the amount of Al/Si and Ca/Si, CAH and calcium silicate hydrate (CSH) are formed at the same time, which according to Fig. 9 reduces the voids and compaction of the soil structure has become (Roshni and Jeyapriya, 2017); which was previously confirmed by the CBR test at long-term curing.

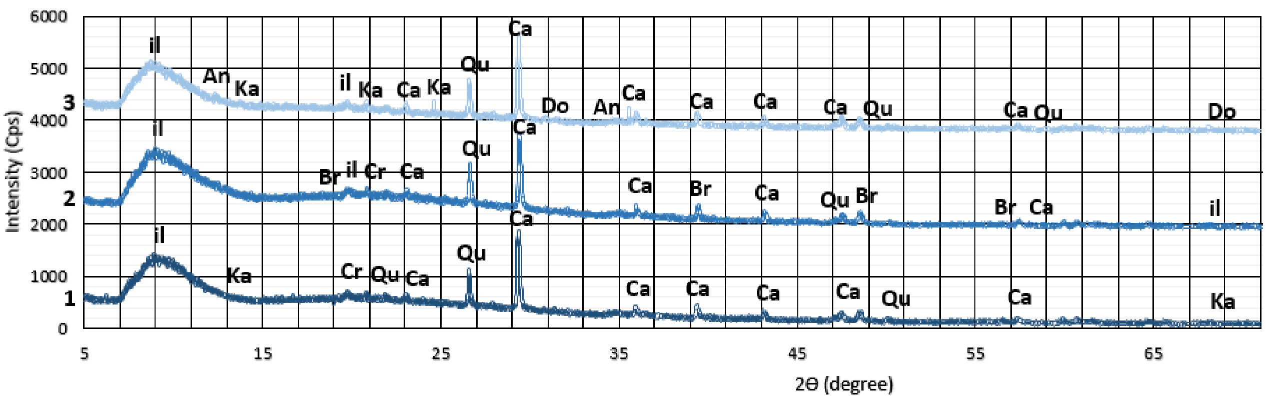
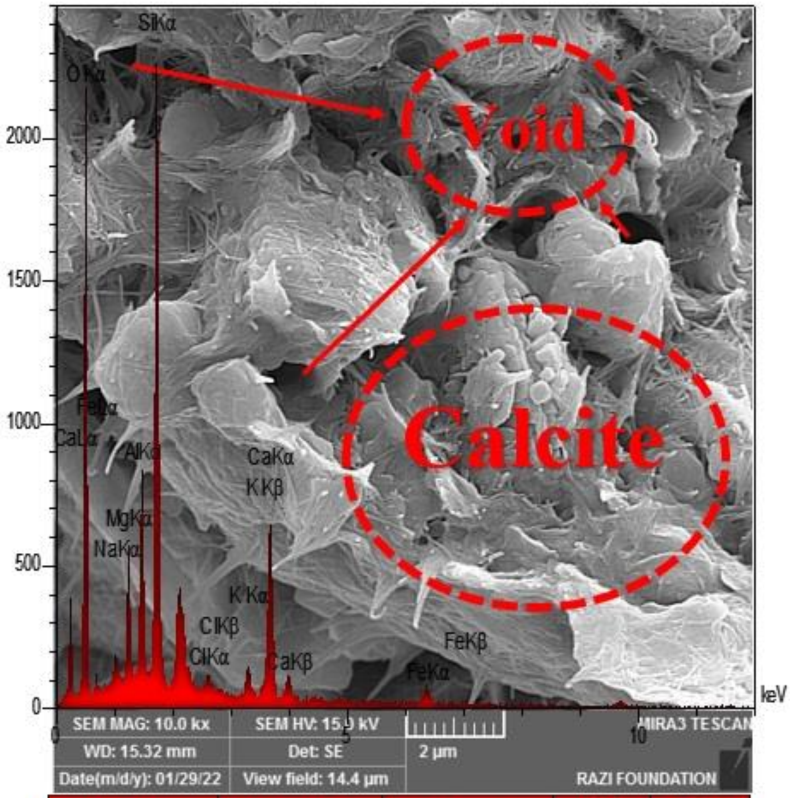
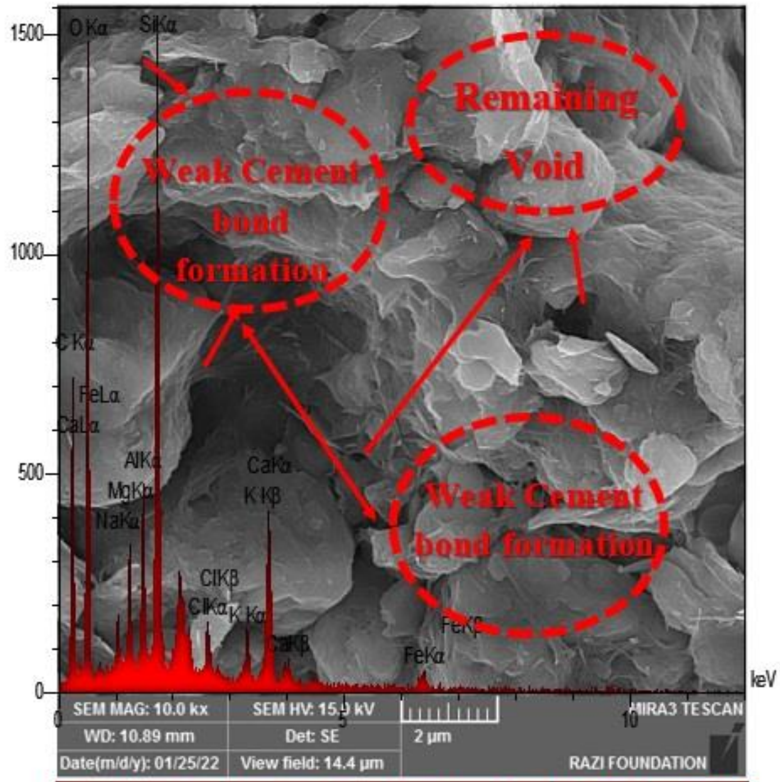


Fig 6. X-ray diffraction pattern of 1: Clay and 2: Clay+15%MSW+1%Nano-MgO; 3: Clay+25%MSW+1%Nano-MgO at curing=120 days (il: illite, Ka: Kaolonite; Cr: Cristobalite; Qu: Quartz; Ca: Calcite; Br: Brucite; An: Anortite; Do: Dolomite)



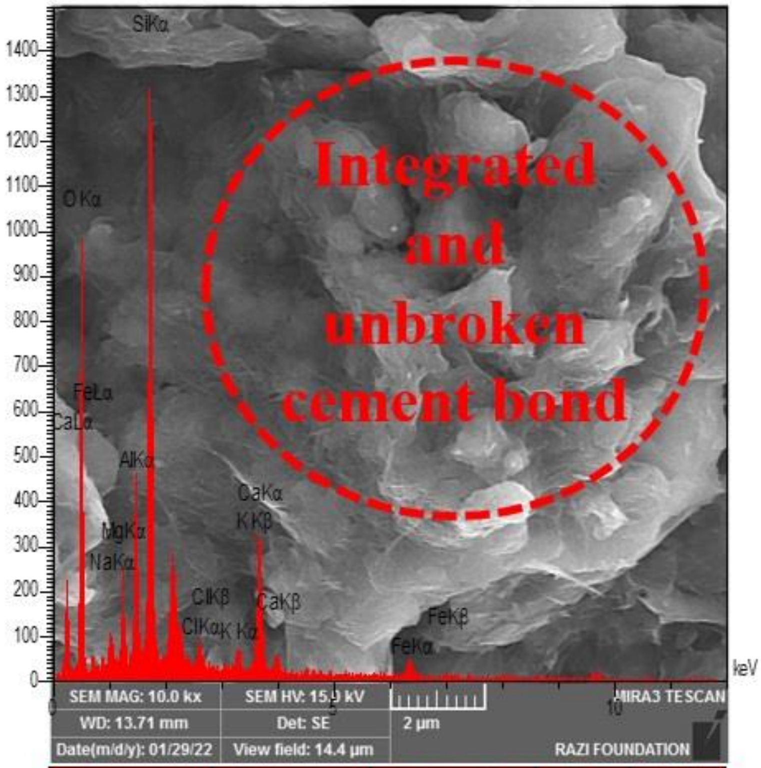
AL (Atomic%)	Si (Atomic%)	Ca (Atomic%)	Al/Si	Ca/Si
5.65	15.78	10.22	0.36	0.65

Fig 7. SEM images & EDS graphs of Clay at curing=120 days



AL (Atomic%)	Si (Atomic%)	Ca (Atomic%)	Al/Si	Ca/Si
2.41	7.63	5.36	0.31	0.70

Fig 8. SEM images & EDS graphs of Clay +15%MSW+1%Nano-MgO at curing=120 days



AL (Atomic%)	Si (Atomic%)	Ca (Atomic%)	Al/Si	Ca/Si
5.84	18.45	9.54	0.32	0.52

Fig 9. SEM images & EDS graphs of Clay+25%MSW+1%Nano-MgO at curing=120 days

4. Discussion

The expansion of MSW is increasing day by day with a rise in population. The improper disposal of MSW releases methane which is more responsible for global warming and also it affects the health condition of the surrounding people. It is the need of the hour to identify the effective use of municipal solid waste as by-products or as a replacement material in the civil engineering field. So the MSW is introduced as an environmentally eco-friendly resource that can utilize as a soil stabilizer to diminish the harmful impacts of these waste materials.

This research tried to investigate the effect of rejected MSW on the behavior of Clay. We also examined the effect of factors such as Percentage of MSW, long-time age, type of experimental and microstructure analysis on the amount of waste reduction. The outcomes of this research offer an encouraging implication for the opportunity of the application of the MSW for stabilizing Clay. This employment disposes of the MSW and reduces using of virgin materials. The insertion of the 15% and 25%MSW+1%Nano-MgO in the soil considerably improved the desired properties of stabilized soil. In general, the UCS properties for stabilized soil increased with 15%MSW+1%Nano-MgO in soil. CBR for the stabilized soil increased as the percentage of the 25%MSW+1%Nano-MgO in the soil increased as well. The rising percentage in the value of CBR touched about 5.59 times in comparison to the unstabilized clay and with minor changes in CBR after 120 days that be attributed to the CBR testing condition. The addition of the MSW to clay greatly affected microstructure. The addition of MSW changed the type of mineral and cement bonds such as C-S-H and C-A-H. The findings of this study are in accordance with (Arunthathi et al., 2022) that showed the compaction characteristic of the problematic soil is modified with MSW in stabilizing the soil and this trend is identical to that of any of the wastes from the industry (Dang et al. 2016; Kamei et al. 2007; Lin et al. 2007; Seco et al. 2011; Bilgin et al. 2012; Mirzababaei et al. 2013; Coudert et al. 2019). Another important references in this field is (Gonzalez et al., 2021) that showed Sewage treatment sludge biochar activated blast furnace slag resulted in 28-day strengths that met European soil stabilisation standards requirements.

The results of the present study showed that MSW has the potential to be usefully used in construction projects such as grade 2 and 3 roads (Arunthathi et al., 2022) and suggests that the MSW has encouraging prospects for replacing Portland cements in soil stabilisation, reducing the carbon footprint of the construction sector and improving the circular economy (Gonzalez et al., 2021) but due to insufficient knowledge in this field and the lack of a plan and lack of sustainable support for this issue from different municipal districts, it has been impossible until now.

5. Conclusions

This study evaluated the potential use and efficacy of soft clay modified with MSW at two curing ages. Different percentages of Nano MgO were also used to stabilize the soft clay containing MSW. Using the UCS and CBR tests, this experimental research provided an acceptable description of the removal of MSW from the environment. The study yielded the following results:

1- Municipal solid waste (MSW) is an eco-friendly additive for soil stabilization so soil stabilization with MSW can manage large volumes of MSW and reduce the carbon footprint of traditional soil stabilization methods.

2- MSW can change the macrostructural and microstructural behaviors of soils and along with Nano-MgO, it can improve soil behavior.

3- Using MSW under the condition of high overhead and confining stress means better soil performance in the long term.

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Conflict of interest

The authors declare that they have no conflict of interest.

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