DOI: 10.38061/idunas.1495204

IDUNAS | NATURAL & APPLIED SCIENCES JOURNAL | 2024 Vol. 7 No. 1 (1-14)

Investigation of the Tensile and Mixed Mode (tensile and shear) Fracture Properties of Cement-stabilized Soils by Numerical Analysis

Research Article

Nazife Erarslan[1*], Pınar Sarı Çavdar[1]

[1] Izmir Demokrasi University, Civil Engineering Department, Izmir, Turkey

Author E-mails:
nazife.dogan@idu.edu.tr
pinar.cavdar@idu.edu.tr
N. Erarslan ORCID ID:0000-0002-5202-9644
P. Sarı Çavdar ORCID ID: 0000-0002-1989-4759

*Correspondence to: Nazife Erarslan, Izmir Demokrasi University, Civil Engineering Department, Izmir, Turkey
DOI: 10.38061/idunas.1495204

Received: 03.06.2024.; Accepted: 20.06.2024

Abstract

In this study, crack initiation, crack propagation, and fracture failure of soil specimens stabilized with cement, an elasto-plastic material, are investigated by numerical analyses. There is no international standard recommended in the literature to find the mode I and mixed mode I-II (tensile and shear) failure values of reinforced soil materials. The aim of this study is to investigate the applicability of ASTM C78, an international standard recommended for concrete specimens, for both indirect tensile and tensile-compression strength tests. Stress and crack analyses in beam specimens were performed using FRANC2D software. The indirect tensile fracture toughness (KIC) value of the modelled beam specimens was found to be 0.32 MPa√m. Similarly, the indirect tensile and shear fracture toughness values were found to be 0.38 MPa√m.

Both non-cohesive and cohesive crack analyses were performed in numerical modeling. Numerical analysis results showed that the most significant slipping between the cohesive crack surfaces was observed in the specimen under mixed mode I-II loading. Moreover, "wing crack" growth in cement-stabilized soil specimens was obtained in numerical modeling in accordance with the principles of fracture mechanics. It is believed that the results of this study will lead to a new international standard for the determination of mode I and mixed mode I-II fracture toughness of cement-stabilized soil specimens.
Keywords: Failure of cement stabilized soil, fractures and reinforced soil, FRANC2D and reinforced soil, cohesive fracture of cement stabilized soil

1. INTRODUCTION

Pavements are a material that distributes the stresses caused by external loads to the lower sections of the road. It is also a layer that reflects deformations and cracks from the road substrates to the surface. Axial

stresses occurring under wheel load cause compressive stress in areas close to the surface. Stresses in the vertical direction in the area immediately below the wheel are diametrical compressive stresses and these stresses cause indirect tensile stresses in the horizontal direction. Compressive stresses in the surface pavement cause rutting deformations, while indirect tensile stresses under the pavement cause tensile and fatigue cracks and deformation. At this point, it is obvious that the principles of fracture mechanics will be very useful in asphalt pavement and road foundation research. In particular, mode I (tensile) and mixed mode I-II (tensile-shear) cracks/defects in fracture mechanics have been reported in many studies in the literature to be very useful in asphalt pavement and asphalt concrete research where such both compressive and indirect tensile and shear stresses occur (Daneshfar et al. 2023).
Stabilized soils are generally used as foundation and sub-base material in road construction. Soil reinforcement with cement is a strengthening process to improve the load-bearing properties of the soil. There are various soil stabilization methods such as mechanical stabilization, chemical stabilization, and compaction to stabilize weak soil (Savran, 1988, Prasad et al. 2015, Fondjo et al., 2021, Zada et al., 2023). However, chemical stabilization with cement is an effective and widely used method to improve weak soil properties. The main aim of soil stabilization with cement is to achieve the necessary improvement in the mechanical properties of the soils in terms of environmental and loading conditions, mostly for transportation structures, water storage structures, building foundations, solid waste storage facilities, etc.

Reinforced soil with cement is an elastoplastic material composed to static loading (Davis 1991, Aliha et al. 2021, Xia et al. 2022, Zada et al. 2023, Xiushan 2023). It is known that indirect tensile and shear stresses develop in asphalt bituminous base and subbase materials under compressive stress applied by the wheel load and the asphalt pavement and foundations material loading (Crockford and Little 1987, Sophan and Das 2007, Paul and Gnanendran 2017, Mashaan et al. 2021, Takahassi et al. 2021, Guo et al. 2021, Erarslan 2023, Pietras et al. 2023, Mousavi et al.2024). Therefore, cement stabilized soil is used commonly in road base and compacted subbase materials, and it is very important to investigate its mixed mode (tensile-shear) strength and fatigue properties (Rezaeian et al. 2019, Chen et al. 2020). Fracture mechanics is the study of defects in materials such as notches, cracks and voids that increase the stress intensity and the damage that occurs due to them. The theory of Linear Elastic Fracture Mechanics (LEFM) was first proposed by Griffith (Lajtai 1971). In the theories used in crack analysis, the stress field near the crack tip of an isotropic linear elastic material is given in Fig.1. The maximum tensile stress criterion called 'Maximum Tangential Stress Criterion', which is mainly used in crack analysis, is given in Eq.1 (Aliha et al. 2022):

$$\sigma_{\theta\theta} = \frac{1}{\sqrt{2\pi r}} cos\left(\frac{\theta}{2}\right)\left[K_I cos^2\left(\frac{\theta}{2}\right) - \frac{3}{2}K_{II} sin(\theta)\right] + \frac{T}{2}\left(1 - cos(2\theta)\right)$$

$$\theta_c = 2tan^{-1}\left(\frac{1}{4}\left[\frac{K_I}{K_{II}} - sin(K_{II})\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right]\right) \qquad (1)$$

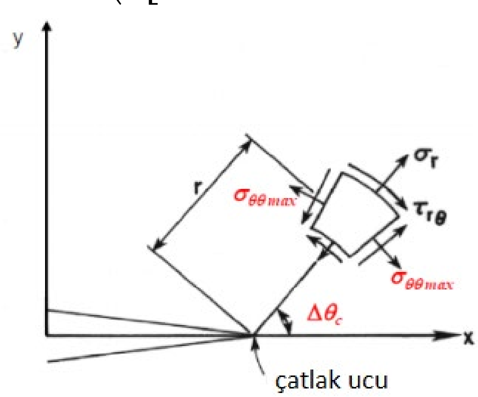


Fig.1 Stress field near the crack tip of an isotropic elastic material

The results obtained in this research will be very important in cement stabilized soil mechanics research. Because cement and lime stabilized soils are semi-friable soils and it will be essential to determine the cracking properties of such materials. It will be very important to be able to intervene in the structure before the final failure, especially in deformation properties under repeated loads and stable crack investigations, which are known as fissure cracks.

1.1 Cohesive Fracturing

Crack formation, propagation and fracture are complementary concepts. The Griffith relation gives values close to reality in glass and brittle materials (Lajtai 2002). However, permanent deformation occurs in metallic materials. Therefore, the energy released in Griffith's criterion is spent in permanent deformation while forming new surfaces. In the 1960s, experimental research on notched concrete specimens showed that parameters such as KIc (fracture toughness) varied depending on the size and geometry of the specimen. These defects of LEFM in practice are due to the presence of the fracture process zone at the tip of the crack, which occupies a larger area compared to other materials. For this reason, some non-linear fracture mechanics approaches have been proposed by some researchers to characterize this region. These models are divided into two categories: cohesive crack models and equivalent elastic crack approaches. Cohesive crack approaches model the fracture process region with a stress block at the crack tip that decreases and compresses the crack, while equivalent elastic crack approaches model it using an effective crack length. A fracture model is developed to determine the critical crack strain at peak load, defined as $\Delta a = a_c - a_0$ (where a_c is the crack length and a_0 is the pre-existing crack length). However, a_c depends on the size of the structure since the critical crack length decreases with increasing specimen size (Bazant 2002). Therefore, nonlinear fracture mechanics approaches recommend the use of at least two parameters for the fracture of concrete.

Stress-induced crack initiation in composite materials, such as cement stabilized soil and reinforced concrete, typically leads to unstable crack growth due to the plastic deformation and the fracture process zobe (FPZ) (Fig. 2) (Dugdale, 1960; Hillerborg, 1977; Behnam, 2021; Ma et al., 2022, Shahbazian and Mirsayar 2023).

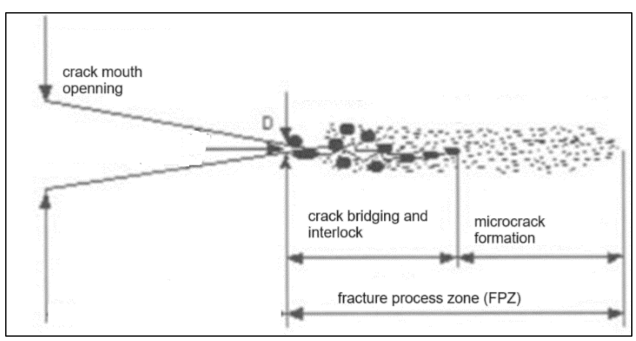


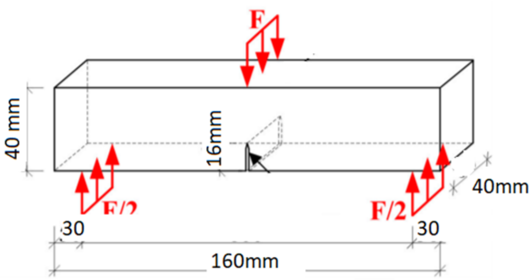
Fig. 2 Fracture process zone (FPZ) at the tip of a crack

2. MATERIAL AND METHODS

In this research, both stress analyses in the specimen and crack analyses were performed by a discrete finite element analysis program FRANC2D. In order to determine the mode I fracture mode, the notch crack was placed at the centre of the beam specimens. For shear and indirect tensile-shear loading, two notches were placed at specified distances from the centre. A specimen prepared with the beam specimen geometry and notch dimensions used is shown in Fig.3. Thus, a three-point bending test was performed by placing two supports below and a single support above the centre.

In this study, numerical analysis and modelling were carried out using the Fracture Analysis Code (FRANC2D) software. Tangential stress concentration theory is used in FRANC2D analyses (Erdoğan and Sih, 1963). While experimental studies reveal the final failure plane and surface cracks that lead to failure, such programs are highly valuable as they allow for the observation of the initiation and propagation trends of microscale cracks and regions with high stress concentrations within the tensioned sample through numerical analyses like the FRANC2D program.

CASCA software was used for modelling specimen shape and mesh structure. Beam specimens were modelled as 30mmx30mmx160mm consistent with the indirect tensile tests (Fig. 3). The modeled beam geometry was fixed in both the x-horizontal and y-vertical directions at two support roller locations beneath the specimen in the experiments (Fig.3).



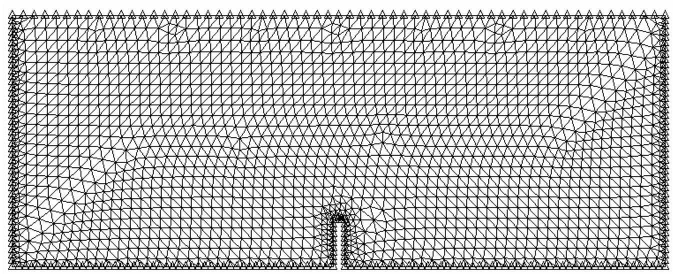


Fig.3. Beam specimen dimensions, specimen geometry and mesh generation using CASCA

Fracture toughness of beam specimens is calculated by three-point bending test and fracture toughness equation is as floows:

$$K_{IC} = 3(P_{max} + 0.5W)\frac{S(\pi a_c)^{\frac{1}{2}}F(\alpha)}{2d^2 b} \quad [\mathrm{Nm}^{-3/2}] \tag{2}$$

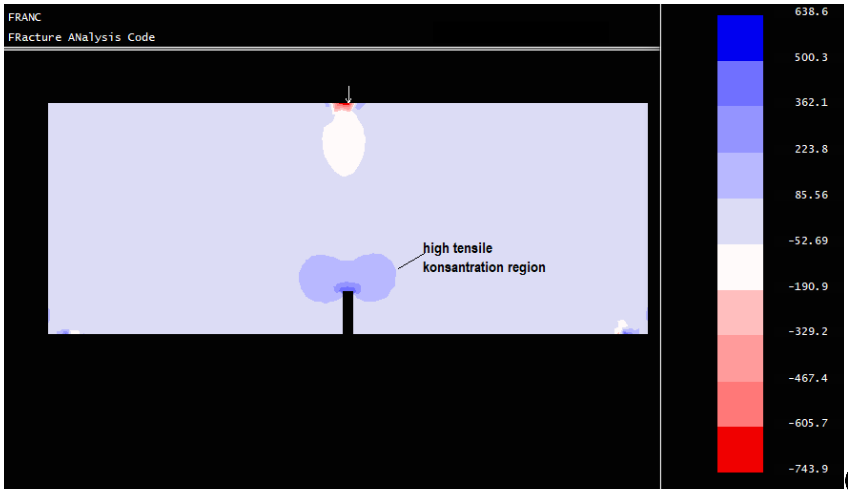
$$F(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{\sqrt{\pi^{1/2}}(1+2\alpha)(1-\alpha)^{3/2}}$$

Where: α=ac/d, ac: notch crack length (mm), P_{max} ultimate failure load [N], d: beam width (mm), L: beam length (mm), W: beam thickness (mm), S: distance between two supports (mm).

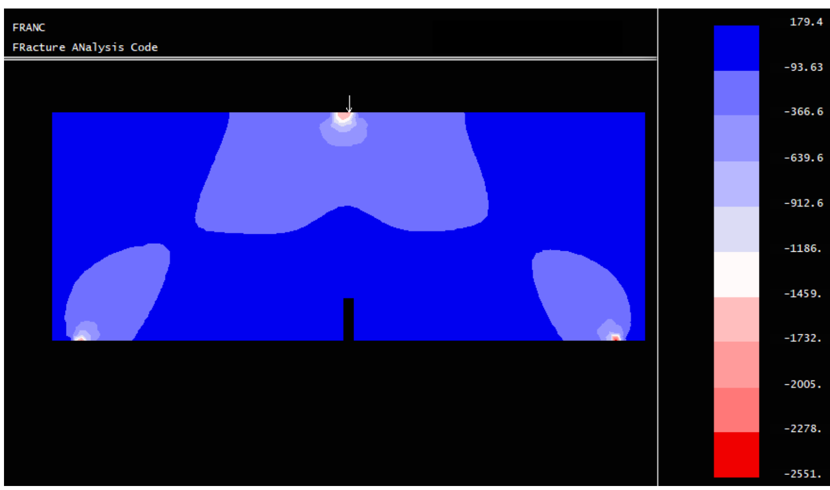
.

RESULTS AND DISCUSSION

The first series of modellings were performed to analyze the conjugate stresses around the pre-existing cracks in the beam specimen before the fracture analyses. In numerical modelling with FRANC2D, the load applied to the beam specimen was applied to obtain indirect tensile stresses. The results of mode I and mixed mode I-II stress distribution analysis for beam geometry specimens are shown in Fig.4 and Fig.5 respectively. When the results of the stress analyses were examined, tensile stress concentration was determined at the notch crack tip under indirect compressive stress in mode I condition. When the minimum principal stress analyses are examined under the same loading condition, compressive stress concentration in areas other than the crack tip and the shear stress is expected to occur in these areas (Fig.4 a and b). In Fig.4c and d, these stress concentrations are shown with 'stress bars' which is one of the FRANC2D post process options.



(a)



(b)

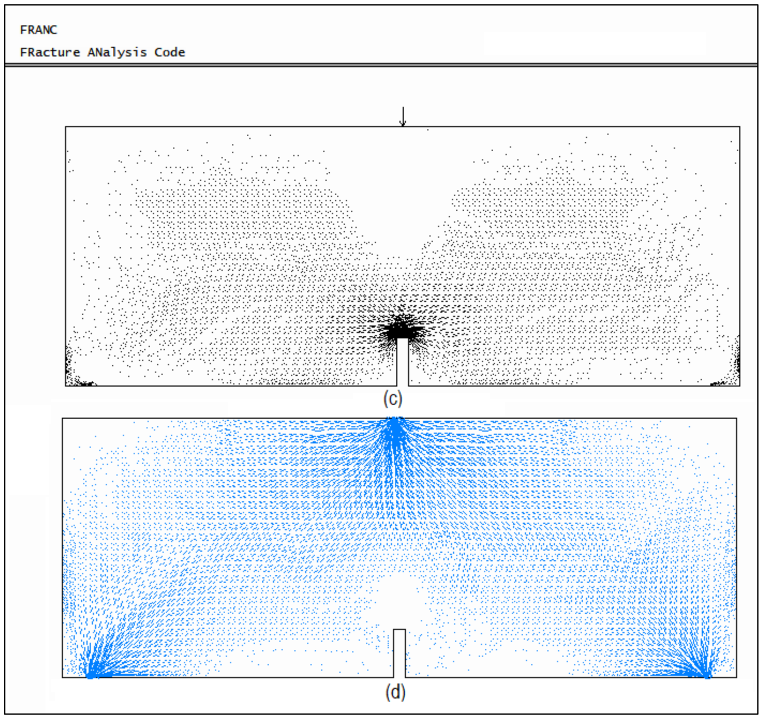
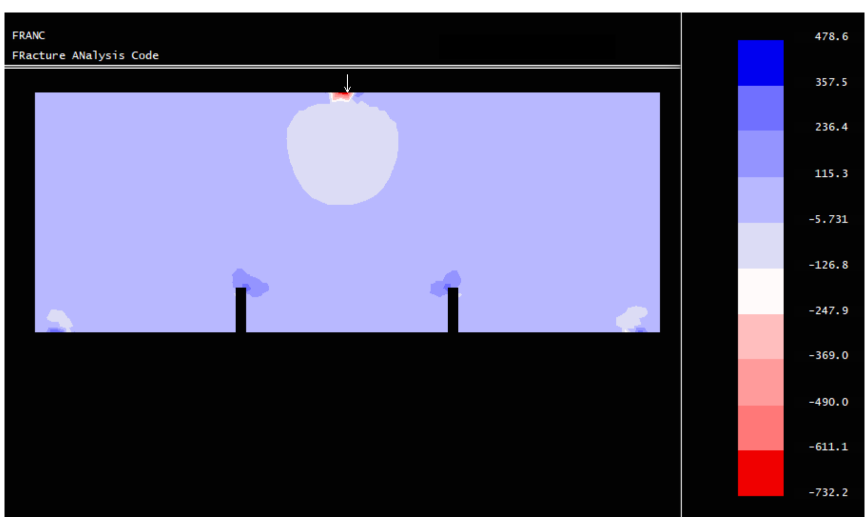
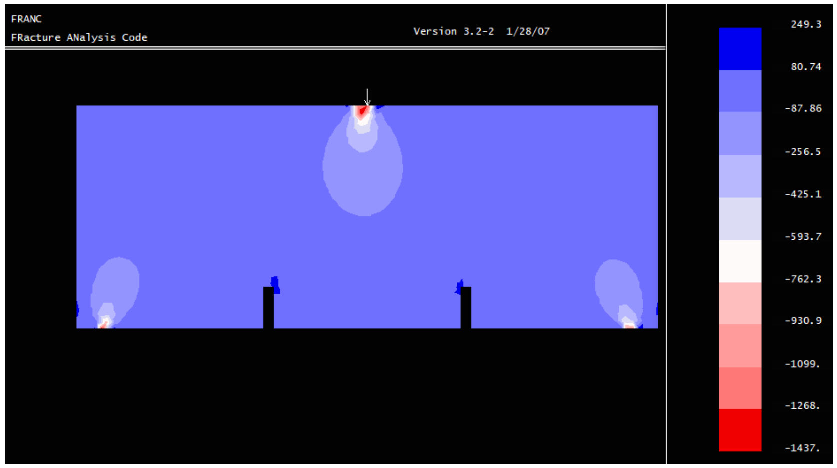


Fig.4 Mode I stress distribution in the beam specimens obtained by FRANC2D program (+: tensile; -: compressive) (a) maximum principal stress (tensile) distribution, (b) minimum principal stress, c) indirect tensile stress zone, d) compressive stress concentration zones

On the other hand, when the stress analysis results were examined, it was determined that indirect tensile stress was developed at the tip of crack under indirect compressive stress in mixed mode I-II, but these regions were shifted from the center to the loading axis at the crack tip (Fig. 5a-b). When the minimum principal stress analyses are examined under the same loading condition, compressive stress concentration in areas other than the crack tip and the shear stress is expected to occur in these areas. In this case, 'wing cracks' mentioned in fracture mechanics are expected to form in these regions (Whittaker et al. 1998). In Fig.5c and d, these stress concentrations are shown with 'stress bars' which is one of the FRANC2D post process options.



(a)



(b)

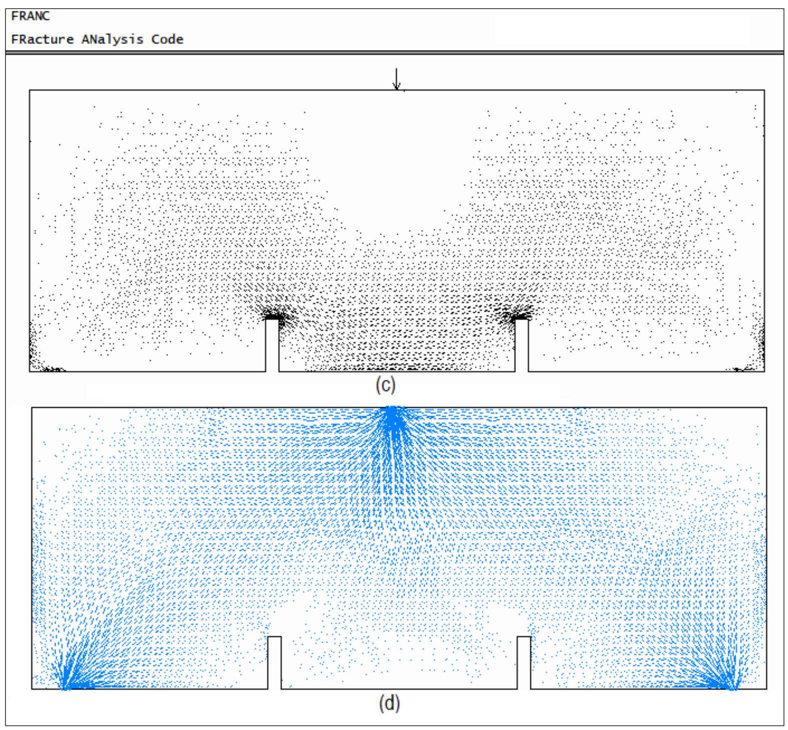
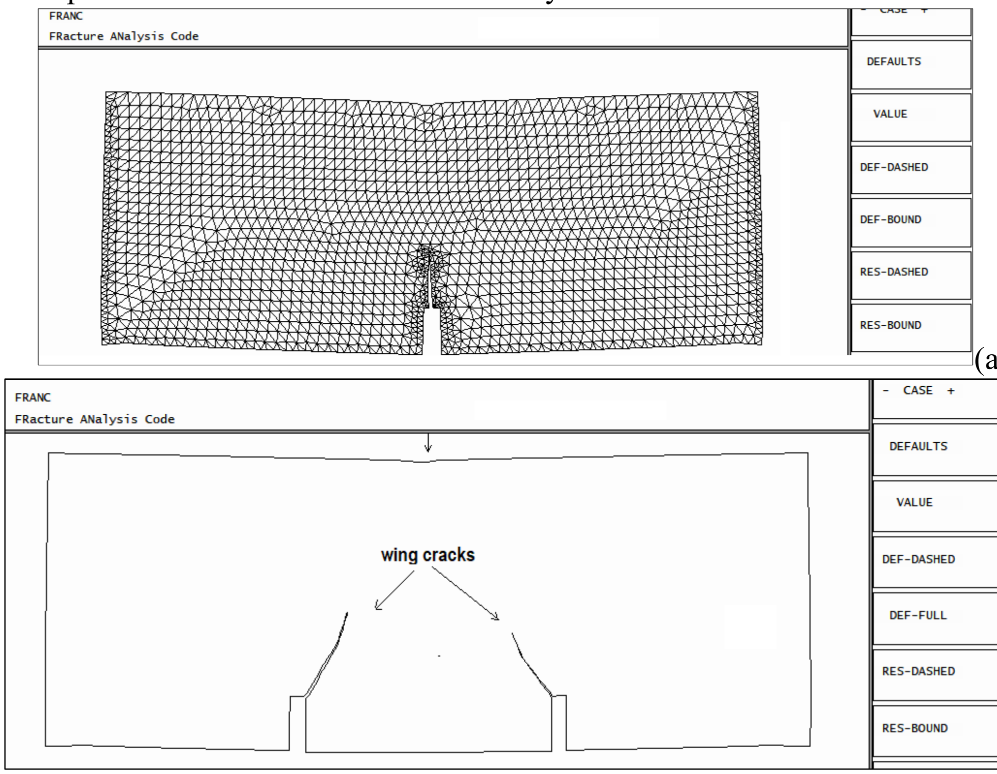


Fig.5 Mixed mode I-II stress distribution in the beam specimens obtained by FRANC2D program (a) maximum principal stress (tensile) distribution, (b) minimum principal stress distribution, c) indirect tensile concentration zone, d) compressive stress concentration zones

The second series modelling to analyze the fracture characteristic of material were conducted. One of the notable advantages of FRANC2D is that during fracture analysis, the mesh generated at the crack tip is removed at each crack propagation step. Subsequently, the program automatically generates a new mesh structure around the crack tip based on the new stress state. FRANC2D is a program that can successfully model elastoplastic fracture analyses.The fracture characteristic of the beam specimen under mode I and mixed mode I-II loading condition is shown in Fig.6a and b respectively.
The crack formation at the pre-existing crack tip in the material under mode I loading by considering the principles of fracture mechanics moves towards the loading axis. As e seen in Figure 6a, the crack formed and propagated in accordance with the principles of fracture mechanics. On the other hand, in the material under mixed mode I-II loading, the crack that develops at the pre-existing crack tip grows towards the

loading axis and propagated in the form of a 'wing crack'. As seen in Fig. 6b, the wing cracks propagated within the beam specimen in accordance with the theory.



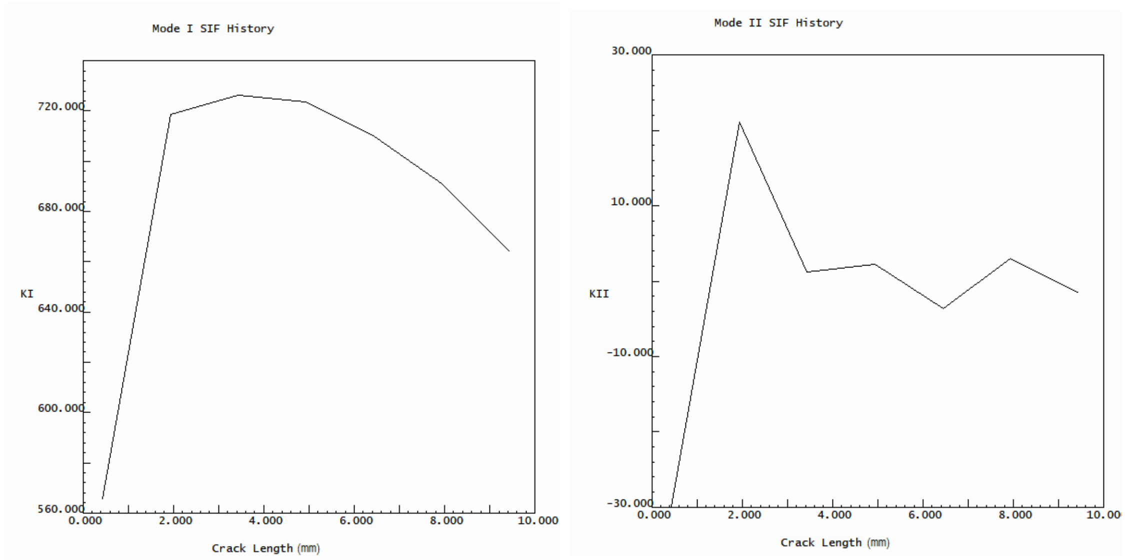
(a)

(b)

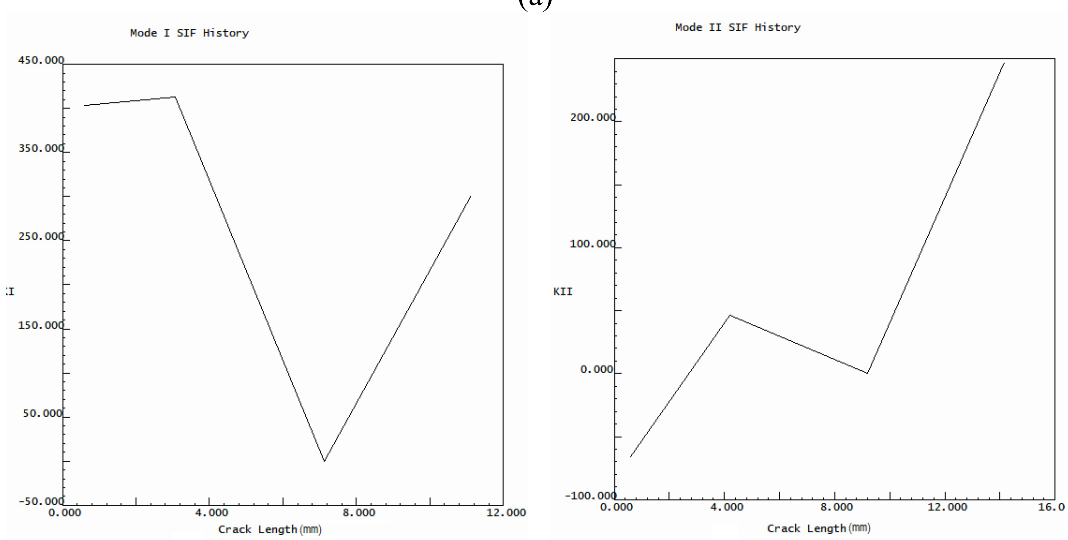
Fig.6 Crack propagation with a) mode I loading and b) mixed mode I-II loading

Alternative of as seen it is stated that As seen in both the colored contour representation in Fig. 4 and the graphical representation in Figure 7, the peak indirect tensile stress was obtained by modelling disinclined crack. It is observed that the maximum tensile SIF value (KI) obtained in the mixed mode I-II case of the modelled crack is considerably lower than the maximum SIF value obtained with mode I (Fig.7a). This result is in accordance with the principles of fracture mechanics because mode I loading develops very high tensile stresses while mixed mode loading develops shear stresses as well as tensile stresses. During mixed mode I-II tests, the tensile force applied to the specimen forces the crack tip to damage in both the opening and sliding directions. This compound loading causes the plastic zone to be more inclined than in the Mode I loading case. Although the plastic zone in Mode I/II is geometrically different from Mode I, its reactions to the change in crack length and deformation rate are similar to those in Mode I loading. On one hand On the other hand, the maximum shear SIF value (KII) obtained under mixed mode I-II loading is considerably higher than the shear stress value obtained under mode I loading (Fig.7b). The mode I (tensile) fracture toughness (KIC) value of the cement stabilized soil specimens was found to be 0.32 MPa√m. On the other hand, the mixed mode I-II fracture toughness value was found to be 0.38 MPa√m.

It is believed that the calculation of fracture toughness of cement stabilized soil will lead to experimental research when fracture mechanics tests are used with these research results. It will be possible to form specimens using molds with cement stabilized soil specimens and it will be possible to prepare specimens by creating notch cracks as in this research or semi-circular bending specimens as in the literature.



(a)



(b)

Fig.7 SIF values in font of the notch crack for a) mode I loading condition and b) mixed mode I-II loading condition

Linear elastic fracture mechanics (LEFM) is confined to the elastic zones, including very small plastic damage. However, NEFM fracture mechanics approaches are necessary when the inelastic/plastic damage is large enough to affect the relative elasto-plastic dimensions, such as the FPZ in front of a notch crack tip. Stress-induced crack initiation in composite materials, such as informal, alternatives: including, for example. such as cement stabilized soil and reinforced concrete, typically leads to unstable crack growth due to the plastic deformation and the FPZ (Fig. 8a). The cohesive crack model is a well-known fictitious crack approach (Figure 8b) used to model cohesive fracture in numerical analyses (Dugdale, 1960; Hillerborg, 1976; Behnam, 2021; Ma et al., 2022, Bittencort, 1993). FRANC2D is a fracture mechanics programme that can model plastic deformation and strain softening in front of the crack tip. Following Dugdale's work, Barenblatt (1959) studied the combined forces at the molecular scale that occur in the region pointed out by Dugdale (1960). In 1976, Hillerborg et al. (1976) proposed a model similar to the one developed by Barenblatt (1959). However, the concept of tensile strength has been introduced instead of the molecular scale solution. Hillerborg's model allowed existing cracks to grow and, more importantly, initiate new cracks. This model is called the "Fictitious Crack Model" (Hillerborg et al., 1976). This developed model is considered the beginning of the development of the cohesive interface model to simulate sudden crack growth in brittle solids.

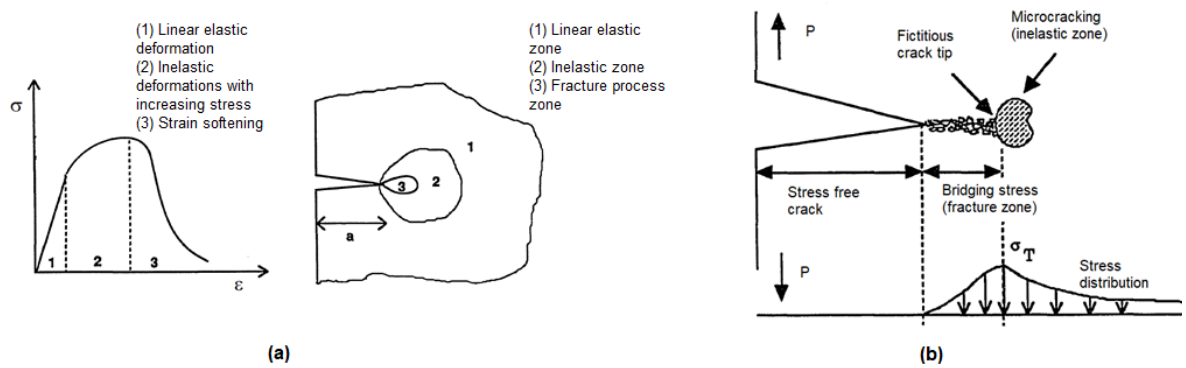


Fig. 8. (a) Fictitious damage zones in front of a crack (b) Fictitious crack model

In numerical analyses, non-linear analyses are very important for modelling the elastoplastic damage zone. In numerical non-linear (fictitious cracking) analyses, NL interface elements for mixed mode I-II fracture are predefined in the program. With these NL elements, the initiation of new cracks and the propagation of existing cracks are modelled. The nonlinear interface elements of FRANC2D are used to model plastic deformation under external load (Fig. 9). The fictitious crack propagation with FRANC2D occurs when the maximum circumferential stress at the tip is exceeded.

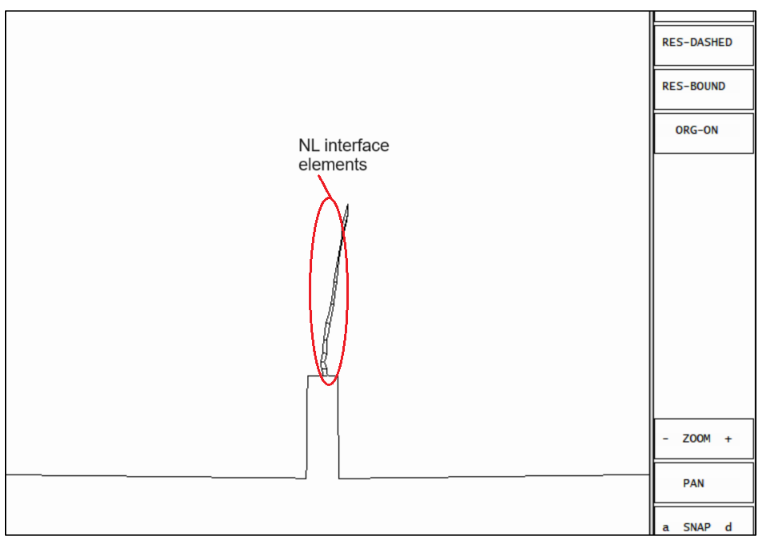


Fig.9 Modelling of fictitious crack propagation

The fictitious crack lengths and the sliding between crack plains for the beam specimen under indirect tensile loading modeling is shown in Fig.10. As seen in Figure 10, cohesion due to friction on the crack surfaces increases up to 3 mm crack length and then continues to decrease. In this case, it is explained that the increase in KI given in Fig. 7 up to this crack length is due to these cohesive forces. When the same analysis was performed for beam specimens under shear-tensile stress condition, it was found that the sliding value between the cohesive crack surfaces was about ten times higher than in the mode I case

(Fig.11). This result is expected and it is stated that the sliding values are higher due to the higher shear forces in the mixed mode I-II case.

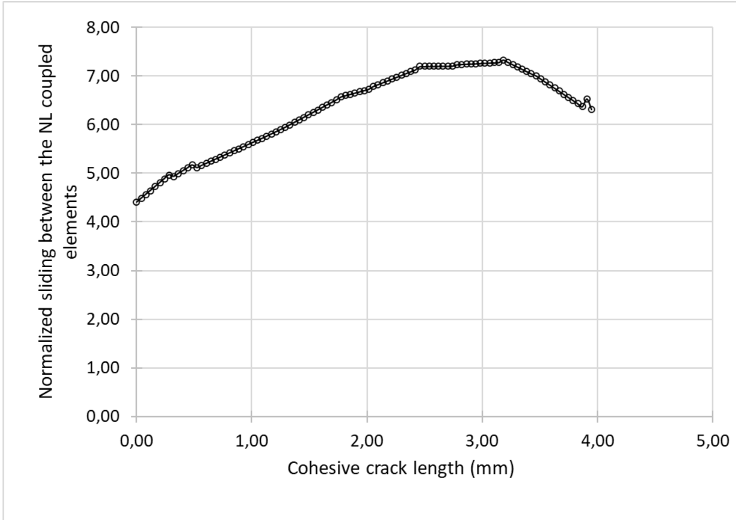


Fig.10 Sliding between crack surface plains for mode I loading

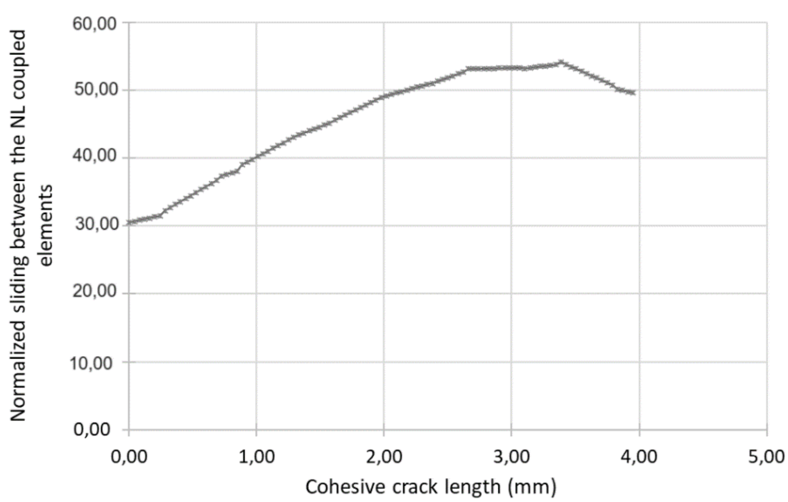


Fig.11 Sliding between crack surface plains for shear-tensile loading

According to the results obtained after cohesive fracture analyses and SIF analyses, it will be very important at this point to investigate and introduce appropriate mixed-mode fracture models and theories for the prediction of fracture properties of soils or soft geo-materials. Because is not proper. Thus, Because, although there are many international standard test methods to find the fracture toughness of cement and metals, no international standard test has been developed for the fracture toughness test of cement stabilized soils, which is a deficiency in the field of mechanics of materials. It is possible to develop mode I and mixed mode I-II fracture models and theories for the prediction of fracture properties of stabilized soils or soft geo-materials using the notched beam specimen or semi-circular disc specimens mentioned in this research.

It is recommended to study different types of industrial and environmentally friendly sustainable cement mixtures in future cement stabilized soil studies. Because cement stabilized soils are mainly used in road construction, but also in deep soil mixing (DSM) and jet grouting (JG) applications. Therefore, considering that millions of tons of cement will be used, it is essential to investigate new generation environmentally friendly cements in terms of fracture mechanics principles in terms of climate change and sustainability. For example, OYAK Cement Ltd., which is the producer of enrironment friendly cement NOVOCEM, has kept the reduction of CO_2 emission with calcined clay technology in the first place among its targets in parallel with borderline carbon applications and produces NOVOCEM© cement with 40% lower CO2 emission and 35% less energy consumption with 20% renewable fuel.The cement sector is responsible for 8% of CO_2 emissions from greenhouse gases in the world. Global climate change and sustainability require the cement industry to seek innovative solutions. Innovative methods aiming to reduce the environmental footprint of cement production have a critical role in the development of the sector.

Soil reinforcement with cement is also very common in underground and tunneling applications. For example, in the so-called umbrella reinforcement, it is a technique that aims to improve the ground around the tunnel during the excavation of the tunnel. It is usually applied using a series of holes into which a cement mixture is injected. In the method, cement is injected into the pipes placed in the ground to increase its strength. Moreoevr, the combination of Sodium Silicate injection and cement would provide effective results in soil improvement and water management processes within tunneling projects. This method is particularly applicable in tunnels where the cement-water mixture cannot control the pressure of groundwater. The cement-water mix can reduce its density due to ground-borne water action and can be washed before setting when in contact with water.

5. CONCLUSION

In this study, the fracture toughness and cracking behavior of soil specimens stabilized with cement, an elasto-plastic material, were investigated. Numerical analyses of stress condition and fracture behaviour were performed using FRANC2D program. Stress and crack analyses in beam specimens were performed using FRANC2D software. The indirect tensile fracture toughness (KIC) value of the modelled beam specimens was found to be 0.32 MPa√m. Similarly, the indirect tensile and shear fracture toughness values were found to be 0.38 MPa√m.

The failure and fracture behaviour of the beam samples under indirect tensile and indirect tensile-shear loading were analyzed for both non-cohesive and cohesive fracture by numerical modeling with FRANC2D. The results of the analyses showed that the most significant slippage between the cohesive crack surfaces was observed in the specimen under indirect tensile-shear loading. The "wing crack" growth in the reinforced soil specimens was obtained compatible with the fracture mechanics applications. The results obtained in this study are expected to bridge over in the development of a new international standard test method for the determination of fracture toughness of reinforced soil specimens under tensile and shear loads.

REFERENCES

1. AlihaM.R.M., Haghighatpour P.J., Tavana A. (2022). Application of asymmetric semi-circular bend test for determining mixed mode I + II fracture toughness of compacted soil material, Eng. Frac. Mech., V.262, 108268
2. Aliha MRM., Kucheki H.G., Asadi M.M. (2021).On the use of different diametral compression cracked disc shape specim ens for introducing mode III deformation. Fatigue & Frac. Eng. Mat. & Struc. 44(11), 3135-3151
3. Bazant Z. (2002) Concrete Fracture Models: testing and practice. *Eng. Frac. Mech. 69,* 165-205
4. Behnam Z. (2021). Crack Front Shape Evolution in Structural Components subjected to Fatigue Loading. University of Adelaide, School of Mechanical Engineering, Australia
5. Bittencourt, T.N. (1993). Computer simulation of linear and nonlinear crack propagation in cementitious materials. Ph.D. Thesis, Cornell University, Ithaca, N.Y

6. Chen X., Yuan, J., Dong, Q., Zhao, X. (2020). Meso-scale cracking behavior of Cement Treated Base material, *Constr. and Build. Mat., V. 239(1–2),* 117823
7. Crockford, W.W., and Little D.N.. (1987). Tensile Fracture and Fatigue of Cement-Stabilized Soil. *J.l of Trans. Eng.,* V. 113(5), 520–537. https://doi.org/10.1061/(ASCE)0733-947X(1987)113:5(520).
8. Daneshfar M, Hassani A, Aliha MRM, Sadowski T. (2023) Assessment of the Specimen Size Effect on the Fracture Energy of Macro-Synthetic-Fiber-Reinforced Concrete. *Materials*, 16(2):673.
9. Davis J. (1991). Fracture characteristics of cement-stabilized soils. *J. Mat. Sci. V.26,* 4095–4103
10. Dugdale, D. S. (1960). Yielding of steel sheets containing slits*, J. Mech. Phsy. Solids, 8,* 100- 104
11. Erarslan, N. (2023). Investigation of the tensile-shear failure of asphalt concrete base (ACB) construction materials using a non-linear cohesive crack model and critical crack threshold analysis. *Const. and Build. Mater., V.364*, 129901
12. Erdogan, F.,Sih G.C. (1963) On the crack extension in plates under plane loading and transverse shear *J. Bas. Eng.,* 85D, 519-527
13. Fondjo, A.A., 2021. Theron, E. R., P. Ray Stabilization of expansive soils using mechanical and chemical methods: a comprehensive review. *Civ. Eng. Arch., 9,* 1295-1308
14. Guo, Q., Chen, Z., Liu, P., Li, Y., Hu, J., Gao, Y., Li, X. (2021). Influence of basalt fiber on mode I and II fracture properties of asphalt mixture at medium and low temperatures. *Theor. Appl. Fract. Mech., V.112,* 102884.
15. Hillerborg, A., Modeer, M., and Petersson, P.E. (1976). Analysis of crack formation and crack growth in concrete by m eans of fracture mechanics and finite elements, *Cement and Conc. Res., V.6* ,773-782.
16. Lajtai EZ. (1971) A theoretical and experimental evaluation of the Griffith theory of brittle fracture. *Tectonophysics, 11,* 129-156
17. Ma, Z., Liu,W., Li, S., Lu, X., Bessling, B., Guo, X., Yang,Q. (2022). A local to global (L2G) finite element method for efficient and robust analysis of arbitrary cracking in 2D solids, *Comp. Meth. in Appl. Mech. and Eng., V. 398*, 115205,
18. Mashaan, N., Karim, M., Khodary, F., Saboo, N., Milad, A. (2021). Bituminous Pavement Reinforcement with Fiber: *A Review. Civil. Eng., V. 2,* 599–612. https://doi.org/10.3390/ civileng2030033
19. Mousavi S.R., Ghasemi M., and Dehghani M. (2024). Investigating the fracture toughness of the self compacting concrete using ENDB samples by changing the aggregate size and percent of steel fiber. *Eng. Solid Mech., 12(1), 17-26*
20. Paul, D. K., and Gnanendran C. T.. (2016). Characterization of lightly stabilized granular base materials using monotonic and cyclic load flexural testing. *J. Mater. Civ. Eng. 28 (1),* 04015074.
21. Pietras D., Aliha M.R.M., Hadi G. Kucheki, Tomasz S. (2023) Tensile and tear-type fracture toughness of gypsum material: Direct and indirect testing methods, J. Rock Mech. and Geotech. Eng. V.15(7), 1777-1796
22. Prasad, A.S.C.V. and Redy, C.S.V. (2015). Strength characterıstıcs of cement stabılızed well graded gravel. Conference: Indian Geotechnical Conference 2015, Pune, India.
23. Rezaeian, M., Ferreira, M.V., Ekinci, A. (2019). Mechanical behaviour of a compacted well-graded granular material with and without cement, *Soils and Foundations, V. 59(3),* 687-698
24. Savran, K.Z., (1988). Stabilization of Cohesive Soils with Fly Ash, Orta Doğu Teknik Üniversitesi Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, Ankara, 62.
25. Shahbazian B. and Mirsayar M.M. (2023). Fracture mechanics of cellular structures: past, present, and future directions. Eng. Solid Mech., 11(2), 231-242.
26. Sophan K., Das, B.M., (2007). Durability of soil–cements against fatigue fracture. *J Mater Civ Eng, 19 (1),* 26-32
27. Takahassi, H., Omori S., Asada H., Fukawa H. (2021). Mechanical Properties of Cement-

Treated Soil Mixed with Cellulose Nanofibre. *Appl. Sci., V.11(14),* 6425, https://doi.org/10.3390/app11146425

28. Whittaker B.N., Singh R.N., Sun G., (1992). Rock Fracture Mechanics - Principles, Design and Applications", Elsevier, Amsterdam.
29. Xia B., Zeng, L., Ji, F., Xie, M., Hong, Z. (2022). Plasticity role in strength behavior of cement-phosphogypsum stabilized soils, .J. *Rock Mech. and Geotech. Eng., V. 14(6),* 1977-1988
30. Xiaokang, Z., Qiao, D., Xueqin, C., Haihang, H., Tianjıe, T. (2021). Evaluation of fatigue performance of cement-treated composites based on residual strength through discrete element method. *Const. and Build. Mater., V. 306*, 1, 173-198
31. Zada, U., Arshad J., Iqbal M., (2023). Sayed M. Eldin, Meshal A., Souhila R.B, Sultan A. Recent advances in expansive soil stabilization using admixtures: current challenges and opportunities, *Case Studies in Constr. Mater.,* V. 18, e01985