

ASSESSING MORTAR MIXES FOR RETROFITTING DAMAGED RC COLUMNS

F.M. Layas ^a, R. E. Suleiman ^a, V. Karakale ^{b,*}, A. Al-Drussi ^a

^a Department of Civil Engineering, Faculty of Engineering, University of Benghazi, Benghazi Libya,
E-mails: fathi.layas@uob.edu.ly; resuleiman@yahoo.com; durssi@gmail.com

^{b*} Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Istanbul Medeniyet University, Istanbul, 34720, Turkey, E-mail: vail.karakale@medeniyet.edu.tr

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ABSTRACT:

Columns are essential structural elements that support the weight of a building. If they fail, the entire structure can become unstable. This study examines three different types of mortar to determine which is most effective for reinforcing and repairing damaged columns exposed to uniaxial compression. The research focuses on war-damaged buildings in Benghazi, Libya, aiming to find the best mortar Mix for structural rehabilitation. Each mortar mix was designed to strengthen columns under two stress conditions: one where the load is applied until cracks first appear and another where the load continues until total failure. The study evaluates key factors such as compressive strength and flexibility to determine how well each mortar Mix stabilizes damaged columns and prevents further deterioration.

1. INTRODUCTION

The structural integrity of columns is vital for ensuring the overall stability of buildings, particularly in post-conflict areas where war-related damage has significantly weakened their load-bearing capacity. This study evaluates the effectiveness of three different mortar Mixes (outlined in Section 3) for retrofitting damaged columns subjected to uniaxial compression. The goal is to determine the most suitable mortar composition for improving the resilience and durability of compromised structures in Benghazi, Libya. To replicate real-world stress conditions, the research examines the performance of these mortar Mixes under two uniaxial compression loading scenarios:

1. Partial Damage Scenario: Columns are loaded until the first signs of cracking appear, then repaired with the selected mortar Mixes and re-tested.

2. Complete Failure Scenario: Columns are loaded until structural failure occurs, repaired using the three mortar Mixes, and subsequently re-tested.

By assessing the effectiveness of these mortar Mixes in structural rehabilitation, the study offers valuable insights into their impact on restoring stability. Key parameters analyzed include load-bearing capacity, deformation characteristics, and overall structural performance. A total of 18 test columns (detailed in Section 4) were vertically cast in wooden molds and subjected to uniaxial compression testing using a 300-ton capacity machine (Figure 1). Nine columns were tested until the onset of initial cracking, while the remaining nine were loaded to complete failure. Afterward, all columns were retrofitted with the selected

mortar Mixes and re-tested to failure to assess improvements in their structural performance.

By examining compressive strength and deformability, this study aims to determine the most effective mortar composition for strengthening war-damaged columns, ultimately contributing to the resilience and restoration of buildings in post-conflict regions.



Figure 1. 300-Ton capacity compressive testing machine

2. REVIEW OF EXISTING RESEARCH

Extensive research has explored various retrofitting and jacketing techniques to improve the strength, stiffness, and ductility of reinforced concrete (RC) columns under axial and lateral loads. Key studies have investigated factors such as preloading, dowel use, surface roughening, and jacket design, providing valuable insights into optimizing retrofitting strategies. Bousias et al. (2007a) examined six different interface treatments, including

* Corresponding author: Vail Karakale, Professor, Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Istanbul Medeniyet University, Istanbul, 34720, Turkey, E-mail: vail.karakale@medeniyet.edu.tr.

dowels and surface roughening, concluding that combining both methods does not significantly enhance performance compared to using them individually. Julio et al. (2008) found that when the bending moment-to-shear force ratio exceeds 1.0, surface treatment is unnecessary for monolithic behavior, provided the jacket thickness remains below 17.5% of the column width. The effects of preloading on retrofitted columns have also been widely studied. Sengottian et al. (2012) and Takeuti et al. (2008) reported that preloaded circular columns exhibit greater ductility due to improved confinement, while Vadoros et al. (2006b) demonstrated that preloaded columns show higher strength and displacement capacity under cyclic loading. However, Mourad et al. (2012) found that excessive preloading diminishes strengthening efficiency, with capacity gains decreasing as preloading levels increase. Shear connectors have been identified as crucial elements in retrofitting strategies. Lampropoulos et al. (2008) demonstrated that their use enhances the strength of layered columns, creating a monolithic-like behaviour. Achillopoulou et al. (2013) highlighted that dowels improve slip resistance but may also accelerate failure by propagating damage from preexisting cracks. Vadoros et al. (2008) noted that welding stirrup ends provides superior strength compared to dowel-only techniques. Rodriguez et al. (2001) observed a threefold increase in strength and stiffness in jacketed columns under seismic loading, though ductility remained unchanged. Sezen et al. (2011) suggested that distributing loading across the entire cross-section enhances axial capacity. Ersoy et al. (1993) found that cyclic loading reduced rigidity by 40% compared to monotonic loading, demonstrating the significant impact of load history on structural performance. Further research has examined alternative retrofitting methods. Chang et al. (2014) compared RC jackets with wing walls, concluding that the former provided superior flexural and shear strength along with better energy dissipation. Pellegrino et al. (2009) studied polymer-modified mortar jackets and found that thin layers (15 mm) tended to debond prematurely, emphasizing the need for durable interface treatments.

3. MORTAR TYPES UTILIZED IN THIS STUDY

In this research, three distinct types of mortar Mixes were employed to examine their properties and performance under various conditions. Each Mix was specifically formulated to highlight unique characteristics and facilitate comparative analysis:

Mix 1: This was a conventional mortar mix (1:3/4 sand to cement ratio by volume) prepared without the inclusion of fiber reinforcements. It served as the control group in the study, providing a baseline for evaluating the impact of modifications introduced in the other mixes.

Mix 2: This variant incorporated fiber reinforcement into the mortar (1% by volume). The addition of fibers aimed to enhance certain mechanical properties, such as tensile strength, crack resistance, and durability, compared to the standard mix.

Mix 3: This formulation utilized a specialized grout known as Sika Grout 214; a product engineered for high-performance applications. Sika Grout 214 is renowned for its advanced properties, such as improved workability, higher compressive strength, and superior bonding capabilities, making it suitable for challenging construction scenarios. Details of the 3 Mixes are presented in Table 2.

Mix type	Contents	Weight	Remarks
Mix 1 without Fibers	Cement (kg)	15	
	Sand (kg)	20	
	Water (kg)	5	
	Super plasticizer (ml)	50	Cap of gallon
	Repaired Columns (Mix No. 1)	T1, T2, T3, P1, P2, P3	
	Date of Repair	21/11/2020 (Saturday)	
	Cement (kg)	15	
Mix 2 with Fibers	Sand (kg)	20	
	Water (kg)	5	
	Super plasticizer (ml)	50	Cap of gallon
	Fibers (kg)	0.01	
	Repaired Columns (Mix No. 2)	T4, T5, T6, P4, P5, P6	
	Date of Repair	21/11/2020 (Saturday)	
	Cement (kg)	15	
Mix 3 Sika Grout 214	Sika Grout 214 (kg)	25	
	Water (kg)	3. May	
	Super plasticizer (ml)	50	Cap of gallon
	Repaired Columns (Mix No. 3)	T7, T8, T9, P7, P8, P9	
	Date of Repair	21/11/2020 (Saturday)	

Table 2. Mixes Used for Repairing the Tested Columns

4. TEST COLUMNS IN STRUCTURAL PERFORMANCE EVALUATION

In this study, all test columns were constructed with a uniform square cross-section of 150 x 150 mm and a height of 1200 mm, ensuring standardized geometry for controlled and consistent testing conditions. This uniformity allowed for reliable comparison of structural performance across different repair methods. The concrete design mix used for constructing the test columns is detailed in Table 3. Each column was reinforced longitudinally with four steel bars, each with a diameter of 8 mm. These bars were symmetrically positioned within the concrete, providing essential support to resist compressive forces and improve the column's overall load-bearing capacity. To further enhance structural integrity, lateral reinforcement was incorporated using stirrups designed to control lateral expansion and improve column stability under compressive loads. Two stirrups, each 2.48 mm in diameter, were grouped closely to create an effective combined diameter of 3.5 mm. These grouped stirrups were spaced 125 mm apart along the column's height, providing uniform lateral reinforcement along its length. This consistent spacing helped manage potential lateral deformation and prevented premature failure, Figure 4.

Category	Parameter	Unit	Value
Mix Design	Water-Cement Ratio (w/c)	–	0.60
Mix Design	Cement	kg/m ³	350
Mix Design	Water	kg/m ³	210
Aggregate Properties	Fine Aggregate Volume	m ³	0.40
Aggregate Properties	Fine Aggregate Density	kg/m ³	1620
Aggregate Properties	Coarse Aggregate Volume	m ³	0.80
Aggregate Properties	Coarse Aggregate Density	kg/m ³	1350
Aggregate Absorption & SSD Weight	Sand Absorption	%	0.98
Aggregate Absorption & SSD Weight	Sand (SSD Weight)	kg	654.35
Aggregate Absorption & SSD Weight	Coarse Aggregate Absorption	%	1.54
Aggregate Absorption & SSD Weight	Coarse Aggregate (SSD Weight)	kg	1096.63
Final Mix Proportions	Cement	kg	350
Final Mix Proportions	Water	kg	210
Final Mix Proportions	Coarse Aggregate (10–20 mm)	kg	1096.63
Final Mix Proportions	Fine Aggregate (Sand)	kg	654.35
Mix Ratio (per 1 kg Cement)	Cement	–	1.00
Mix Ratio (per 1 kg Cement)	Water	–	0.60
Mix Ratio (per 1 kg Cement)	Coarse Aggregate	–	3.13
Mix Ratio (per 1 kg Cement)	Sand	–	1.87
Concrete Cylinder Details	Cylinder Volume	m ³	0.005301438
Concrete Cylinder Details	Casting Date	–	06/07/2020
Sample Material Quantities	Cement	kg	12.95
Sample Material Quantities	Water	kg	7.73
Sample Material Quantities	Coarse Aggregate (10–20 mm)	kg	23.96
Sample Material Quantities	Fine Aggregate (Sand)	kg	23.98

Table 3. Concrete mix design for columns



Figure 4. Steel reinforcement of column samples and post-casting of concrete

5. MATERIAL PROPERTIES ASSESSMENT

5.1 Concrete Strength Evaluation

To ensure consistency and accurately assess material properties, 150 mm concrete cylinders were cast alongside the test columns. These specimens underwent standard water curing and were tested for compressive strength at 7 and 28 days. The average results, summarized in Table 5, indicate an average compressive strength of 24.33 MPa at 28 days, serving as a baseline reference for the concrete mix used in column construction.

Category	Parameter	Unit	7-Day Result	28-Day Result
General Info	Date of Test	–	13/07/2020	8.03.2020
	Cylinder Area	mm ²	17.671,46	17.671,46
	Average Compressive Strength	MPa	17,92	24,33
Cylinder 1	Failure Load	kN	300	450
	Weight	kg	12,57	12,79
Cylinder 2	Failure Load	kN	330	420
	Weight	kg	12,7	12,64
Cylinder 3	Failure Load	kN	320	420
	Weight	kg	12,68	12,65
Average	Failure Load	kN	316,67	430
	Weight	kg	12,65	12,6

Table 5. Cylinder Compressive Strength Test Results for Trial Concrete Mix (7 and 28 Days)

5.2 Reinforcement Material Testing

The structural contribution of reinforcement was assessed by testing steel samples from two critical components:

- Longitudinal reinforcing bars (8 mm diameter)
- Lateral reinforcement links (2.48 mm diameter)

Tensile tests were conducted to determine their yield strength, a key factor in evaluating the reinforcement's role in structural performance. The results were as follows:

- Longitudinal reinforcement bars: Yield strength of 188 MPa
- Lateral reinforcement links: Yield strength of 346.87 MP.

6. EXPERIMENTAL PROGRAM

The experimental program in this study was meticulously organized into two distinct phases: Phase I, focused on the initial monolithic casting of columns, and Phase II, centered on the repair and retesting of the damaged specimens. Each phase was designed to capture different aspects of column behavior under compressive loads, allowing for a detailed examination of both original and repaired structural performance.

6.1 Phase I: Monolithic Casting Work

In the first phase, concrete columns were vertically cast using a mix with a cement, sand, and coarse aggregate ratio of 1:1.852:3.086 (Figure 6a). The materials - ordinary Portland cement, beach sand as fine aggregate, and crushed gravel as coarse aggregate - were chosen for consistency. A water-cement ratio of 0.7 was maintained. Alongside the columns, 150 mm cylindrical samples were cast for compressive strength testing after 28 days to establish a reference baseline (Figure 6b). The concrete was poured into wooden molds, compacted using a rubber tube vibrator to eliminate voids, and cured under laboratory conditions. To retain moisture and ensure proper hardening, columns were coated with Sika Antisol WB curing compound. After 24 hours, the molds were removed, and the top surface was smoothed using a rubber plate. The specimens were then cured for 28 days to achieve full strength before testing (Figure 6c). During testing, a 300-ton capacity machine applied uniaxial compression (Figure 6d). The first set of columns (Series T – Total Failure) was loaded continuously until structural collapse establishing baseline failure capacity. The second set (Series P – Partial Failure) was loaded only until initial cracking appeared, marking the onset of structural distress. The loading rate was manually controlled for uniform application across all specimens.



Figure 6.a) Concrete of Testing Columns, b) Cylindrical Specimens Post-testing, c) Column Samples under Curing, and d) Typical Column under Testing

To protect and cure the repaired surfaces, each specimen was coated with Antisol WB, a curing compound designed to retain moisture and aid in the curing process, and then left under stable laboratory conditions. After 28 days of curing, the repaired columns were subjected to a uniaxial load test to determine structural performance. The load was gradually increased until

failure, and the ultimate load capacity for each column was recorded.

6.2 Phase II: Preparation and Retesting of Column Samples

In Phase II, all damaged columns were repaired using different mortar Mixes to restore or enhance their structural integrity. The repaired columns were then re-tested under axial compression to assess improvements in load-bearing capacity and deformability. Proper preparation of the damaged concrete surfaces was essential to ensure effective repairs. All unsound or contaminated concrete, along with any external concrete cover outside the reinforcement cage, was carefully removed using hammer and chisel to expose rough, sound surfaces. Final cleaning involved washing the surfaces to remove dust and loose particles, followed by drying. Sika Bond was then applied to form a strong adhesive layer between the old concrete and the new repair materials. Figure 7 illustrates the specimens at the final stage of preparation, showing surfaces after chipping, cleaning, and the application of the bonding agent. New wooden molds were custom-built to match the exact dimensions of the damaged areas on each column, ensuring a snug fit and uniform repair coverage. The columns were then cast in a vertical orientation.



Figure 7. Column Samples after Failure

After casting, the fresh repair specimens were left to set for approximately 4 to 6 hours, allowing the repair materials to reach initial hardening. Once this phase was complete, the wooden molds were carefully removed, and the column surfaces were smoothed and finished, as shown in Figure 8.



Figure 8. Smoothing and Finishing of Tested Column surfaces

6.3 Axial Deformation Monitoring

To monitor deformation characteristics during loading, a digital strain gauge was installed 300 mm from the top of each column. This gauge measured vertical displacement and strain in real time. By tracking displacement variations, the system helped detect early signs of structural cracking or yielding, providing critical insights into column stability and failure mechanisms. The experimental setup, illustrated in Figure 9, shows the placement of the strain gauge and its connection for continuous monitoring.



Figure 9. Connection of Digital Strain Measurements

7. THEORETICAL PREDICTIONS OF TEST COLUMN CAPACITY

To evaluate the structural capacity of the test columns, we used standard equations to calculate their theoretical load-bearing capacities. According to ACI Code 318-14, the predicted capacity is 43 tons, whereas calculations based on BSI 8110 result in a slightly higher capacity of 44.2 tons. This difference arises primarily due to variations in the coefficients used and the methods for measuring compressive strength in the two standards.

7.1 Load Calculation Formulas

1.ACI Code 318-19 – Nominal Load Calculation

$$P_n = 0.85Acfc' + Asfy$$

2.BSI 8110 (1985) – Ultimate Load Calculation

$$N_{cal} = 0.67fcuAc + Asfy$$

Where:

- fc' – Cylinder compressive strength (measured using 150 mm diameter cylinders)
- fcu – Cube compressive strength (measured using 150 mm cubes $fcu \approx 1.20 \times fc'$)
- Ac – Cross-sectional area of the concrete
- As – Cross-sectional area of the longitudinal steel reinforcement
- fy – Yield strength of the longitudinal steel

These calculations provide valuable insights into the structural performance of the column's compressive strength, ensuring compliance with essential safety and design standards. Notably, the computed theoretical strengths closely align with the experimental results obtained from column testing, as summarized in Tables 10 and 11.

8. ANALYSIS AND FINDINGS

The subsequent sections provide a detailed presentation of the test results, offering a comprehensive analysis of the data obtained. Specifically, the results are examined across both the T (total failure) and P (partial failure) columns to facilitate a clear and comparative evaluation. Key findings and insights derived from this comparative analysis are systematically consolidated in Tables 10 and 11, which summarize the outcomes and conclusions.

8.1 Test Results for Series T Columns

The test results for the ultimate load capacity of the columns in series T, both pre and post retrofitting with various repair materials, are presented in Table 10. This data highlights the comparative effectiveness of the three mortar Mixes (1, 2, and 3) in restoring and enhancing the load-bearing capacity of the damaged columns. Mix 2, the fiber-reinforced mortar Mix, achieved the highest level of retrofitting efficiency. This Mix provided an average failure load capacity across columns T4, T5, and T6 that was 95.1% of the original undamaged column strength.

Column	Before Repair (ton)	Mix Type	After Repair (ton)
T1	47,4	1	36
T2	37,5	1	28,5
T3	36,3	1	27,5
T4	41,1	2	34,8
T5	35	2	33,6
T6	32,5	2	34
T7	39,2	3	31,1
T8	20	3	35,5
T9	37,6	3	29

Table 10a. Results of Tested Columns (T-Type) – Load and Repair Data

Column	Efficiency (%) Avg	Efficiency (%) Ref *	Ntest/Pn	Ntest/Ncal
T1	94,46	80,47	1,1	1,07
T2	74,78	-	0,87	0,85
T3	72,16	-	0,84	0,82
T4	91,31	89,56	0,96	0,93
T5	88,16	-	0,81	0,79
T6	89,21	-	0,76	0,74
T7	81,6	83,62	0,91	0,89
T8	93,15	-	0,85	0,82
T9	76,09	-	0,87	0,85
Overall Avg	-	-	0,98	0,86

Table 10b. Results of Tested Columns (T-Type) – Efficiency and Strength Ratios (* Efficiency of Repair %) (With Respect to Overall Average Failure Load)

In comparison, Mix1, the standard mortar Mix without fiber reinforcement, resulted in an average efficiency of 75.9%, indicating a substantial recovery in strength but lower performance relative to Mix 2. Mix 3, utilizing SikaGrout 214, achieved an intermediate level of repair efficiency, with an average load capacity recovery of 84.66%. This indicates a balanced improvement, providing more strength than Mix 1 but slightly less than Mix 2. In summary, the test results indicate that Mix 2 is the most effective retrofitting option in terms of compressive strength, followed by Mix 3 and Mix 1, respectively.

8.2 Test Results for Series P Columns

Table 11 presents the load data for the columns in series P, showing both the initial cracking loads prior to repair and the ultimate load capacities after retrofitting with different mortar Mixes. An analysis of Table 11 reveals that Mix 2 - the fiber-reinforced mortar - demonstrated the highest repair efficiency in restoring load capacity. The average ultimate load capacity for columns retrofitted with Mix 2 in series P reached 107.49% of

the original, undamaged strength recorded for the series T columns.

This remarkable performance indicates not only a full recovery of strength but a slight enhancement beyond the original structural capacity, underscoring the additional durability provided by the fiber reinforcement in Mix 2.

For comparison, Mix1, the standard mortar Mix without fiber additives, achieved a 92.62% recovery of the original series T strength. While this represents a substantial improvement in structural integrity, it falls short of the enhanced performance provided by Mix 2. Mix 3, which utilized the Sika Grout 214 grout formulation, resulted in an average recovery of 95.86% of the original strength. This performance is stronger than that of Mix 1, but still slightly lower than Mix 2.

Column	Initial Crack Load (ton)	Mix Type	Failure Load After Repair (ton)
P1	25	1	33,3
P2	33	1	30,2
P3	33	1	42,4
P4	20,8	2	38,3
P5	25	2	42
P6	30	2	42,6
P7	25,5	3	43,5
P8	20	3	32,5
P9	33,5	3	33,6
Overall Avg	27,31	–	37,6

Table 11a. Results of Tested Columns (P-Type)- Load and Repair Data

Column	Efficiency Avg (%)	Efficiency Ref* (%)	Ntest/Pn	Ntest/Ncal
P1	87,38	92,62	0,77	0,75
P2	79,24	–	0,7	0,68
P3	111,25	–	0,99	0,96
P4	100,5	107,49	0,89	0,87
P5	110,2	–	0,98	0,95
P6	111,78	–	0,99	0,96
P7	114,14	95,86	1,01	0,98
P8	85,28	–	0,76	0,74
P9	88,16	–	0,78	0,76
Overall Avg	–	–	0,87	0,85

Table 11b. Results of Tested Columns (P-Type) - Efficiency and Strength Ratios (* Efficiency of Repair (%)) (With Respect to Overall Average Failure Load)

A key observation from this data is that the repair efficiency of all mortar Mixes was higher in series P columns than in series T columns. This improvement may be attributed to specific structural characteristics or initial conditions of series P.

In any case, it is clear that Mix 2 offers superior repair effectiveness for both series, while Mix3 provides a moderate improvement, and Mix 1, though effective, remains the least efficient in achieving a full restoration of load capacity. Mix 1 is the most effective option when evaluating both strength and cost efficiency.

8.3 Axial Stress-Strain Behavior of Tested Column (T) Samples

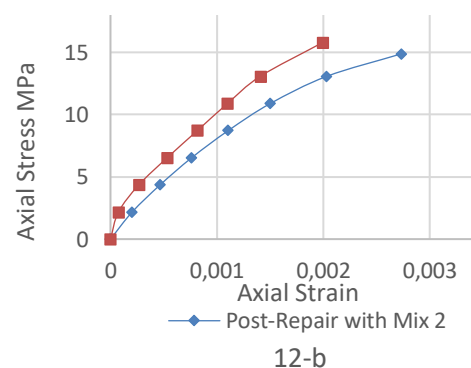
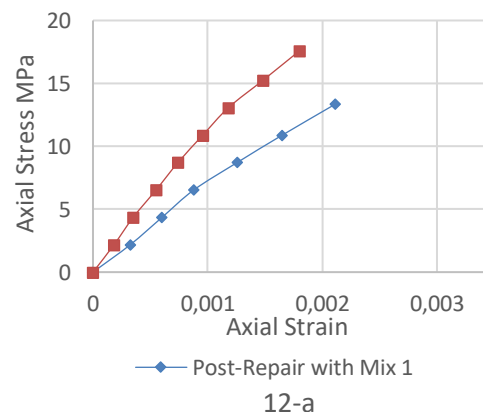
The axial stress-strain relationship for the tested column samples is illustrated in Figure 12. The testing procedure involved loading the columns to failure (T columns), followed by repairs and subsequent retesting until failure. The stress-strain relationships have been analyzed for the following test groups:

- Set 1: Columns T1, T2, and T3, repaired using Mix 1
- Set 2: Columns T3, T4, and T5, repaired using Mix 2
- Set 3: Columns T7, T8, and T9, repaired using Mix 3

The average axial stress-strain diagram for each set is presented in Figure 12. The strain values at peak stress range from 0.0018 to 0.0027. The lower limit (0.0018) is below the typical ultimate concrete strain at failure (0.002) as per the Eurocode.

This reduction in strain is primarily attributed to buckling effects, which significantly influence the failure mechanism. Figure 12 illustrates that Mix 1 and Mix 2 enhance ductility, enabling the columns to endure greater deformation before failure. This improves structural performance and increases resistance to sudden failure.

In contrast, while Mix 3 effectively restores strength, it reduces ductility, making the columns more rigid and more susceptible to brittle failure under load.



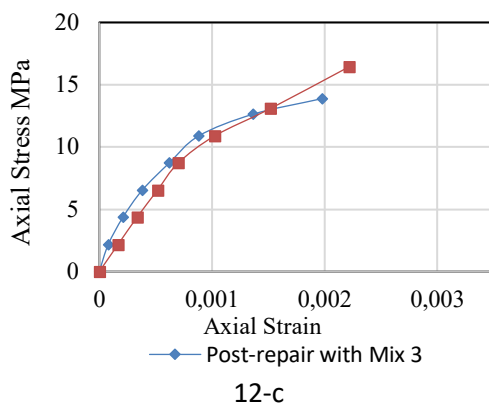


Figure 12. Comparison of Pre- and Post-Repair Average Axial Stress-Strain Relationship of Column Samples a- (T1, T2, T3), b- (T4, T5, T6) and c- (T7, T8, T9)

9. CONCLUSIONS

This research focuses on identifying the most effective mortar composition for strengthening structurally compromised columns.

Three distinct mortar Mixes were tested:

- *Mix 1, a standard mortar without fiber reinforcement;
- *Mix 2, a fiber-reinforced mortar; and
- *Mix 3, utilizing the SikaGrout 214 grout formulation.

The analysis evaluated their performance in terms of compressive strength and deformability to determine their contributions to structural restoration.

The findings revealed significant differences in performance among the Mixes.

Mix 2, the fiber-reinforced mortar, emerged as the most effective, achieving 107.49% for (P columns) and 89.56% for (T columns) of the original strength and providing enhanced durability, making it ideal for maximum recovery applications.

Mix 3, with Sika Grout 214, achieved a moderate recovery of 95.86%, for (P columns) and 83.62% for (T columns) of the original strength making it suitable for tasks where full restoration of strength is not essential.

Mix 1, with a recovery rate of 92.62%, for (P columns) and 80.47% for (T columns) of the original strength was the least efficient but remains a cost-effective solution for budget-conscious projects.

The axial stress-strain relationships for the repaired and retested columns (T columns), (using Mixes 1, 2, and 3) reveal peak strain values ranges between 0.0018 and 0.0027. C

olumns repaired with Mixes 1 and 2 exhibit enhanced ductility, while Mix 3 provides moderate strength improvement but results in a more brittle structural behaviour.

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