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Repair of RC Elements Partially Damaged by Explosions

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This research aims to investigate the effect of using cement grout and epoxy compound in repairing reinforced concrete elements partially damaged by explosions. The research methodology goes through two steps. In the first step, six samples of reinforced concrete slabs are prepared for the laboratory tests. Citorex grout and kema epoxy 103 are used to repair the damage concrete. Tests to measure the deflection and strain due to the maximum load before and after the repair process are carried out. In the second step, four reinforced concrete samples were exposed to a direct explosive force produced by the detonation of 250 grams of TNT, and the effects resulting from the explosion were observed. After that, the repair process was carried out for these samples. Then these samples were exposed again to a second blast force from 250 grams of TNT, and the effects resulting from the explosion were observed.

Keywords: Repair, RC Elements, Damaged, Explosions, Deflection.

1. Introduction

Repair and rehabilitation of existing damaged concrete structures has emerged as one of the most important construction activities globally. In recent times, numerous public and private buildings have suffered destruction due to terrorist attacks and civil wars that have spread across various regions and countries [1-4]. The majority of these buildings have been intentionally targeted for direct or indirect bombardment during conflicts. Concrete, being a fundamental building material, is extensively used in various infrastructure projects including

bridges, roads, and buildings [5, 6]. When these concrete elements are exposed to explosions, their structural integrity is at risk due to the cracks, spalling, and even complete collapses of the concrete elements. The damage is a direct consequence of the explosive forces exerted on the concrete elements [4, 7, 8]. Treating concrete that has been exposed to explosive forces is crucial for preserving its durability, longevity, and ensuring the safety of individuals. When repairing reinforced concrete elements partially damaged by explosions, there are a few key steps that need to be followed. These steps typically involve [9-16]:

• Safety Precautions: Ensure the area is safe to work in and take necessary safety precautions, especially if there is a risk of further explosions or structural instability.

• Assessment: Begin by assessing the extent of the damage and identifying the areas that need repair.

• Cleaning and Preparation: Clean the damaged area thoroughly to remove any debris, loose concrete, and contaminants. This will help to ensure a good bond for the repair materials.

• Reinforcement Repair: If the reinforcement has been damaged, it may need to be repaired or replaced to restore the structural integrity of the element.

• Concrete Repair: Use suitable repair materials, such as high-strength concrete or specialized repair mortars, to fill in and rebuild the damaged areas. Proper application techniques are crucial for a durable repair.

• Finishing: After the repair material has set, finish the surface to match the surrounding concrete and ensure a smooth appearance.

• Protection and Maintenance: Depending on the specific circumstances, additional measures such as applying protective coatings or implementing maintenance plans may be necessary to prevent future damage and ensure the longevity of the repair.

Repairing structural elements that have been damaged by explosions is a complex task that demands expertise in structural engineering and concrete repair. To ensure the safety and effectiveness of the repair work, it is crucial to involve qualified professionals. Their knowledge and experience will help in accurately assessing the damage, selecting appropriate repair methods and materials, and executing the repairs in accordance with industry standards and best practices [17].

It is found that, on the whole, the increase of both cross-sectional thickness and width reduces the concrete spalling damage on the back surface, and the increase of cross-sectional width instead of thickness reduces the concrete spalling damage on side surfaces [8, 18].

Extensive studies during the last five decades have shown that short-duration high-magnitude loading conditions significantly influence structural response. Explosive loads are typically applied to structures at rates approximately 1000 times faster than earthquake-induced loads. The corresponding structural response frequencies can be much higher than those induced by conventional loads. Furthermore, short-duration dynamic loads often exhibit strong spatial and time variations, resulting in sharp stress gradients in the structures. It is known that high strain rates also affect the strength and ductility of structural materials, the bond relationships for reinforcement, the failure modes, and the structural energy absorption capabilities [19]. Therefore, a better understanding of structural behavior under blast loads is very important, and a strong interest exists in developing better approaches to insure improved structural behavior. Repair and rehabilitation of existing damaged concrete structures has emerged as one of the most important construction activities globally [16]. In this study, six samples of reinforced concrete slabs are prepared for laboratory tests using the universal test machine with 100 tons. Three of them are control samples and exposed to load until they collapse, and the remaining three samples are concrete samples subjected to 60-70% of the load to which the control samples that collapsed were exposed. Also, four concrete slabs are prepared with different thickness and exposed to the initial forces to evaluate the strength and durability of the concrete samples. This work was conducted under the supervision of Masam project experts for the removal of mines from Yemeni land. Four reinforced concrete samples 60*60 cm with different thickness were exposed to a direct explosive force from the detonation of 250 grams of TNT, and the effects resulting from the explosion were observed. After that, the repair process was carried out for these samples by using cement grout and Kema epoxy 103. Then these samples were exposed again to a second blast force from 250 grams of TNT, and the effects resulting from the explosion were observed.

2. Materials

2.1 Concrete

The concrete used for six Slabs in this study was sourced from LRM Inc., a ready mix supplier in Lawrence, Kansas. All six specimens were cast using the same batch of concrete. The concrete consisted of limestone aggregate with a maximum size of 13 mm. Detailed information about the concrete properties can be found in Tables 1 and 2.

Table 1: Concrete Mix Proportions

Material	Proportions
Type I Portland cement	279 kg/m3
Water	117 kg/m3
Sand	1028 kg/m3
Class 1, (13 mm) diameter max size limestone aggregate	1004 kg/m3
Air entraining agent	35 gm /m3

Table 2: Concrete Mix Properties

Properties	Value
Water/Cement Ratio	0.42
Target Strength	3500 psi
Unit Weight	2334 kg/m3
Slump	57 mm
Air Content	3%

The compressive strength of concrete was evaluated by conducting tests on cylindrical specimens measuring 150 x 300 mm. The testing procedure followed the guidelines outlined in ASTM C 39. Three samples were selected from the curing room and subjected to testing after 28 days. Table 3 shows the compressive strength values of 150 x 300 mm cylindrical concrete specimens.

Table 3: Compressive Strength of 150 x 300 mm Cylindrical Concrete Specimens at 28 days wet cured

Specimen No.	Individual Cylinder Strength psi	Average Cylinder Strength psi
1	4250	4260
2	4300	
3	4230	

2.2 Repair Materials

1. Citorex Grout

Citorex Grout is a cement-based product designed for repairing cracks and restoring damaged concrete elements. By adding water, it forms a high-strength mortar that does not shrink. This product complies with the American standard specifications outlined in ASTM C1107, ensuring its quality and suitability for various concrete repair applications.

2. Kema epoxy 103

Kema epoxy 103 is a two-component epoxy compound that is solvent-free and primarily used for injecting concrete cracks. It comes in the form of two components that need to be mixed. This product meets the requirements specified in the American standard specifications ASTM C881, ensuring its suitability for concrete crack repair applications. The technical specifications of Kema epoxy 103 at a temperature of 25˚ C are shown in Table 4, offering detailed information about its properties and performance characteristics.

Table 4: Technical specifications of Kema epoxy 103 at 25˚ C

Technical specifications at 25˚ C	limits
Density	1.10 ± 0.02 kg / liter
Mixing ratio A:B by weight	2:1
Initial drying time	8 hours
Final drying time	24 hours
Operating period	45 minutes (decreases as temperature increases)
Bending resistance	500 kg/cm²
Dilute	Keem Solve 4 (5% if needed)

3. Experimental Program

Blast experiment modeling

To identify an appropriate blast loading scenario for a blast incident, empirical or semi-empirical models based on experimental data can be employed to construct blast models. This approach is particularly useful when conducting detailed numerical simulations is impractical or when simplified engineering tools are required. Consequently, it is necessary to scale down both the blast source and the target structure to facilitate the development of these models [4, 20]. The objective is to ensure that the applied treatments effectively address the damaged concrete without causing complete collapse. The experimental work is divided into two parts: Part 1 involves testing concrete samples in the laboratory, while Part 2 focuses on blasting the concrete samples.

Part 1: Testing concrete samples in the laboratory: (by universal test machine with 100 tons)

For laboratory testing, six reinforced concrete slabs were prepared using a universal test machine with a 100-ton capacity. Table 5 displays the dimensions of these samples. The longitudinal and transverse reinforcement was consistent across all slabs. To ensure material consistency, all six slabs were cast simultaneously from the same batch of ready-mix concrete. During casting, a concrete bucket with a chute was used to place the concrete in the forms, and vibration was applied for consolidation. After approximately 72 hours, the forms were removed. Subsequently, the slabs were covered with burlap and plastic and subjected to a curing period of five days. Following curing, the slabs were stored outdoors, exposed to various elements such as direct sunlight and rain.

Table 5: Dimensions of six samples of concrete for laboratory tests

NO.	Symbols	H (cm)	W (cm)	L (cm)
1	S1 (10)	10	40	140
2	S2 (10)			
3	S1 (12)	12	40	140
4	S2 (12)			
5	S1 (15)	15	40	140
6	S2 (15)			

Where:

S1 (H): refers to the control sample in the experiment that was subjected to load until it collapsed.

S2 (H): denotes a concrete sample in the experiment that was exposed to 60-70% of the load applied to the control sample.

The experiment program divided into two steps

Step 1: Before repair

Step 2: After repair

Step 1: Before repair

Figure 1 depicts the typical steel reinforcement used in the tested slabs, providing a visual representation of the reinforcement pattern. On the other hand, Figure 2 showcases the slabs under load conditions at the mid span. In this figure, the strain gauge and steel wire are positioned at the mid span of the tested sample, allowing for the measurement and monitoring of strain and stress levels during the experiment.

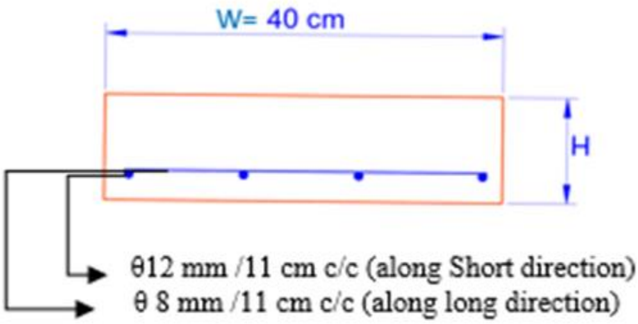

Figure 1: Typical steel reinforcement of slabs

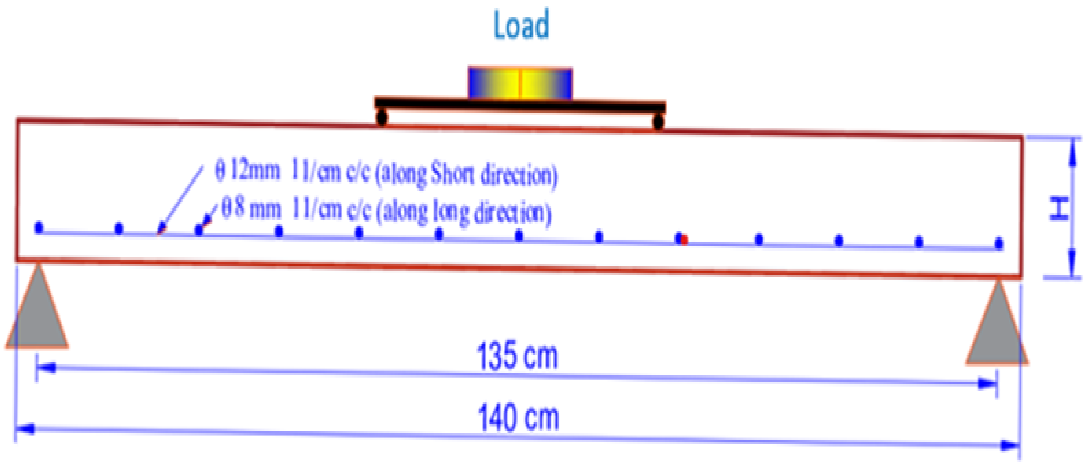

Figure 2: Slab under load

Step 2: Repair the damage slabs then expose them to the same load

During this stage, the concrete samples that had collapsed were repaired using either citorex grout (a mixture of Portland cement, grout cement, sand, gravel, and water cement ratio of 0.5) or Kema epoxy 103. The damaged sections of the concrete were removed, and NDP (presumably an adhesive) was applied to bond the old concrete with the new concrete. After the repair process, these concrete slabs were subjected to testing once again, being loaded with the same load as before, to evaluate their performance.

Part 2: Blasting concrete samples

In the initial phase, four concrete samples (A1, A2, A3, and A4) were created using ordinary Portland cement, gravel, sand, and water. Table 6 provides details regarding the dimensions, cover, height, reinforcements, and the mix ratio of these concrete samples. Under the supervision of Masam project experts, these concrete samples were subjected to a direct explosive force generated by detonating 250 grams of TNT. The resulting effects of the explosion were observed and studied. Figure 3 displays the four concrete samples during the casting process at the site [21].

Table 6: Dimensions and reinforcements of reinforced concrete samples

No.	Dimension in (cm)	Cover in (cm)	Height (Thickness) in (cm)	Reinforcements		Ratio of mix.	Sample
1	60 x 60	2.5 cm In each side	20	Upper Ǿ 12 mm	Lower Ǿ 12 mm	1:2:3	A1
2	60 x 60		15			1:2:3	A2
3	60 x 60		15			1:2:3	A3
4	60 x 60		10			1:2:3	A4

Figure 3: The four concrete samples during casting at site

In the second phase, the concrete samples that sustained damage from the initial blast were repaired. Following the repair process, these samples were then subjected to a second blast with the same force generated by 250 grams of TNT. The effects of this second blast were observed and evaluated to assess the extent of the damage caused.

4. Results

Part 1: Testing concrete samples in the laboratory: (by universal test machine with 100 tons)

1. Before repair

Figure 4 shows the pattern of cracks for specimens after damage and before repair.

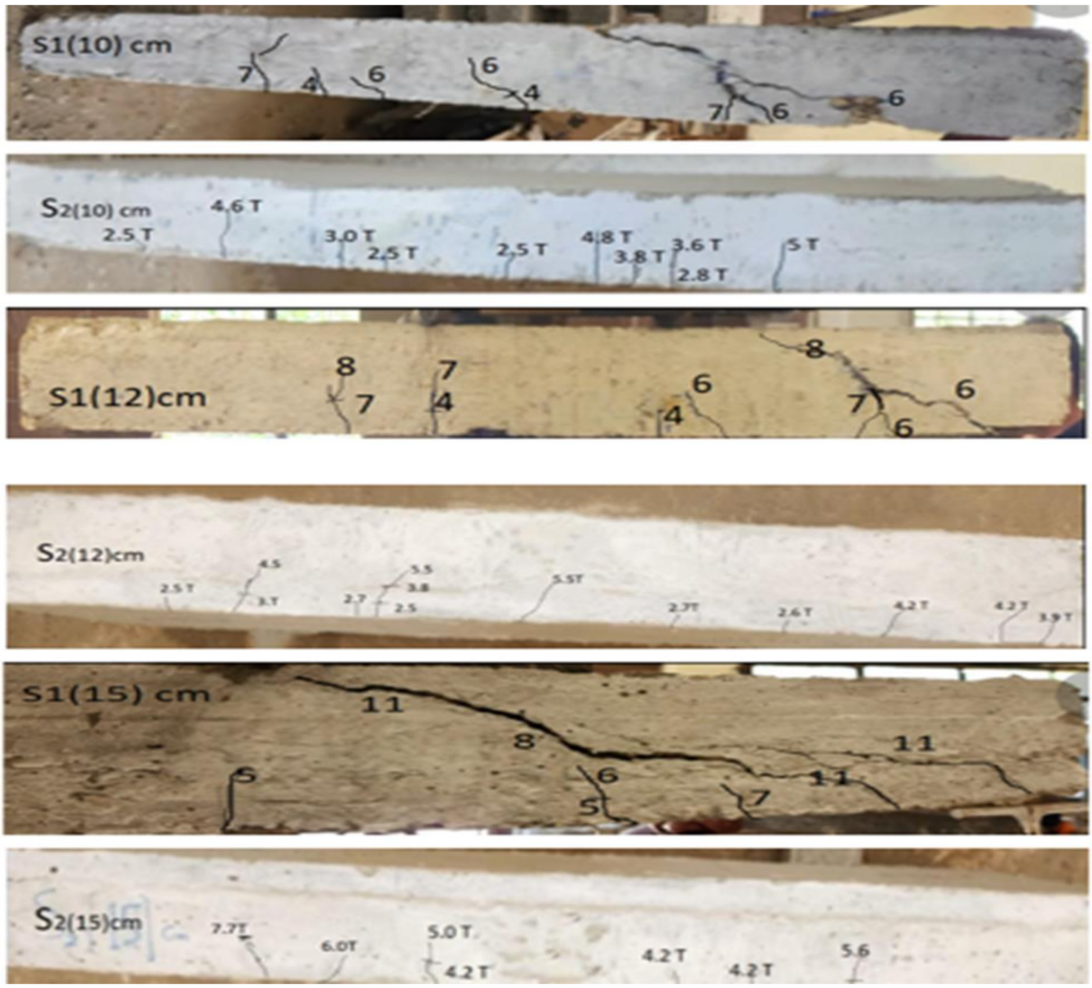

Figure 4: Pattern of cracks for specimens after damage by the first explosion

Figures 5 to 10 display the load-deflection curves for the concrete slab samples S1 (10), S2 (10), S1 (12), S2 (12), S1 (15), and S2 (15) before undergoing repairs. These curves illustrate the relationship between the applied load and the resulting deflection of the slabs. Additionally, Figures 11 to 16 present the load-strain curves for the same concrete slab samples. These curves depict the relationship between the applied load and the corresponding strain in the slabs before any repairs were made.

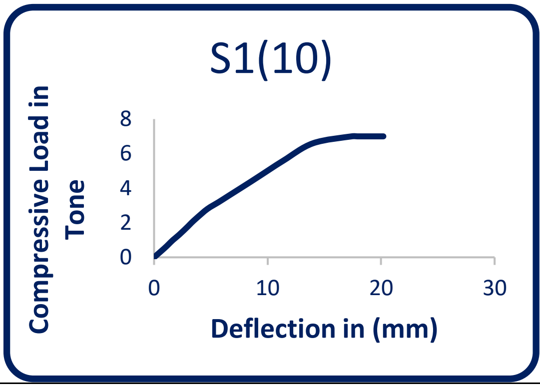

Figure 5: The load-deflection curve for the concrete sample S1 (10) before repair

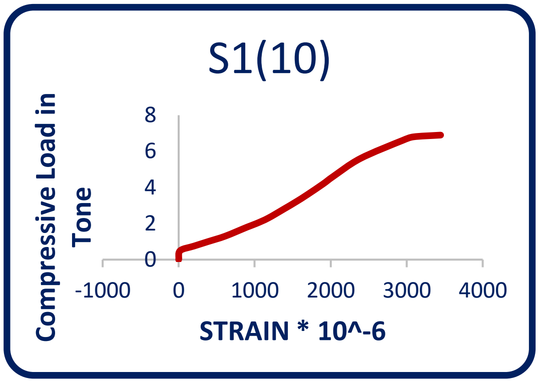

Figure 11 : The load-strain curve for the concrete sample S1 (10) before repair

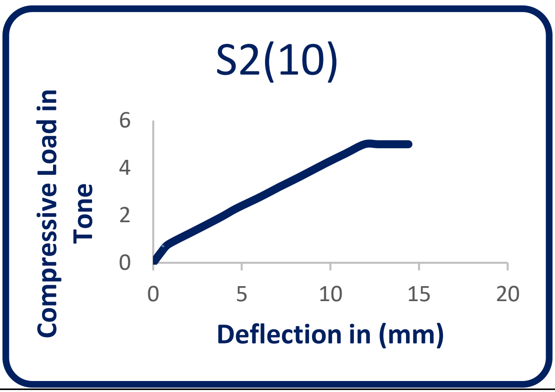

Figure 6: The load-deflection curve for the concrete sample S2 (10) before repair

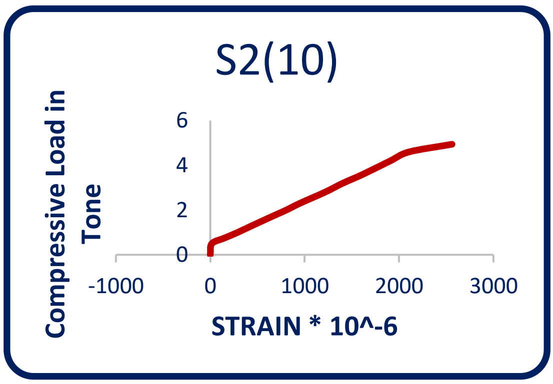

Figure 12 : The load-strain curve for the concrete sample S2 (10) before repair

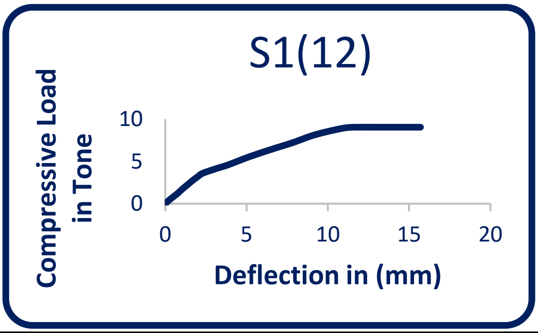

Figure 7: The load-deflection curve for the concrete sample S1 (12) before repair

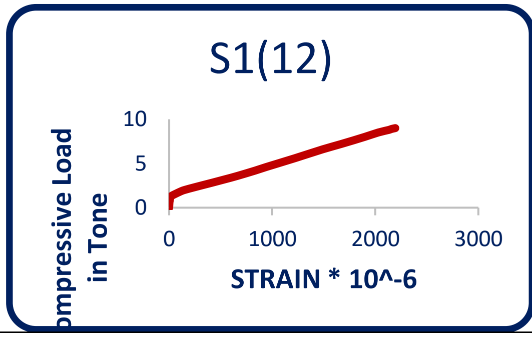

Figure 13 : The load-strain curve for the concrete sample S1 (12) before repair

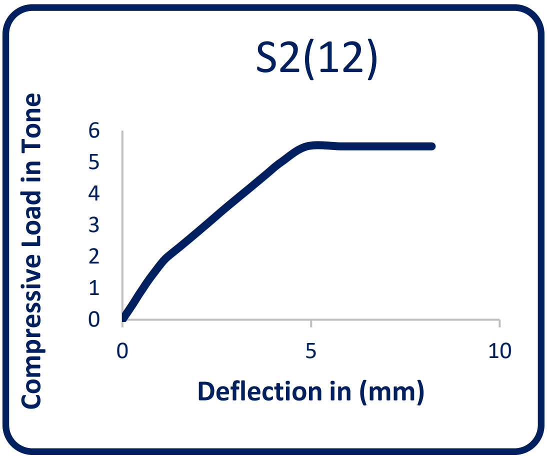

Figure 8: The load-deflection curve for the concrete sample S2 (12) before repair

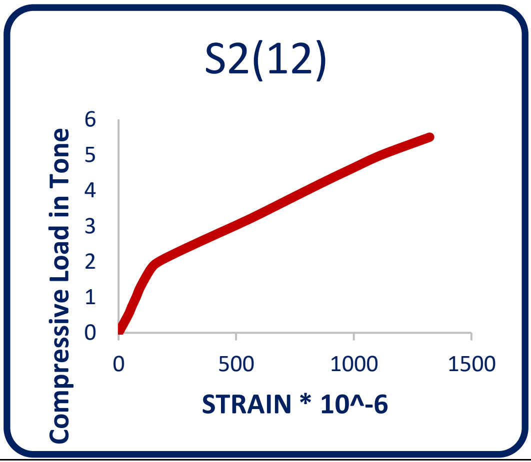

Figure 14 : The load-strain curve for the concrete sample S2 (12) before repair

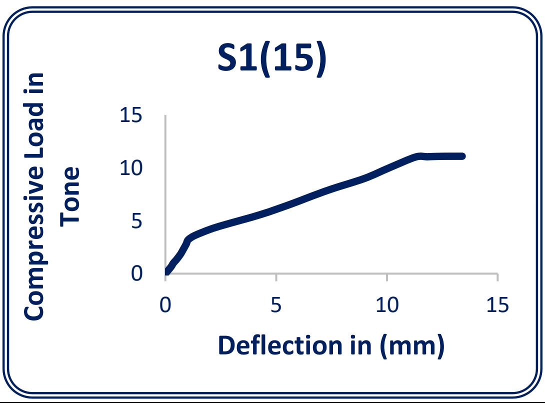

Figure 9: The load-deflection curve for the concrete sample S1 (15) before repair

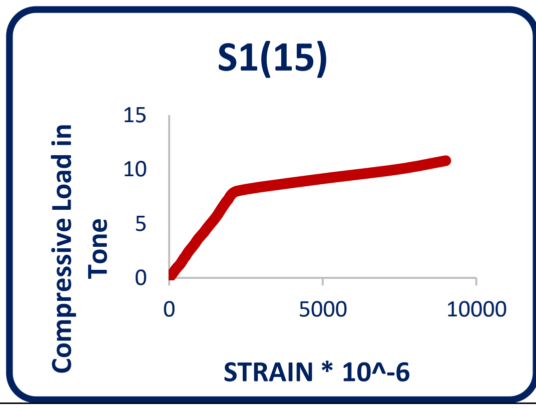

Figure 15 : The load-strain curve for the concrete sample S1 (15) before repair

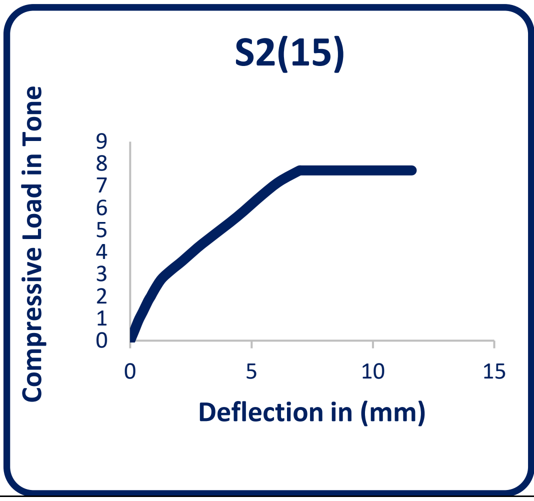

Figure 10: The load-deflection curve for the concrete sample S2 (15) before repair

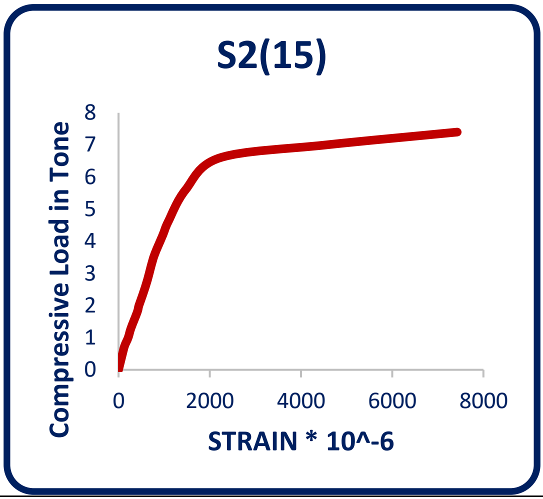

Figure 16 : The load-strain curve for the concrete sample S2 (15) before repair

Step 2: After repair

1. Using Citorex grout to repair the damage in control samples

The control slab samples, namely S1 (10), S1 (12), and S1 (15), underwent the same treatment process for repair. This involved removing the damaged parts of the slabs. Subsequently, a concrete mixture reinforced with Citorex Grout was applied as shown in Figure 4.17, presumably as a repair material.

Figure 17: Repair of the control samples S1(10), S1(12) & S1(15) by using Citorex grout

2. Using Kema Epoxy 103 to repair the damage in other concrete samples

The other reinforced concrete slab samples, namely S2 (10), S2 (12), and S2 (15), underwent a similar treatment approach for repair. This involved slightly enlarging the cracks in the concrete. Subsequently, Kema Epoxy 103, a substance used for repair purposes, was applied using the injection method. The epoxy was left to harden, as depicted in Figure 18, in order to secure and strengthen the repaired areas of the concrete samples.

Figure 18: Repair of the concrete samples S2(10), S2(12) & S2(15) using Kema Epoxy 103

Table 7 shows the results of deflection and strain of concrete samples before and after repair.

Table 7: The results of deflection and strain of concrete samples before and after repair

	Pre-treatment experiments (before repair)					Post-treatment experiments (after repair)				
Concrete samples	Max. load (Tons)	Max. def. With max. Load (mm)	Max. def. after stopped load (mm)	Max. strain	Max. Load of max. strain	Max .load (Tons)	Max def. with max. load (mm)	Max. def. after stopped load (mm)	Max. strain	Max. load of max. strain
S1(10)	7	17.4	20.2	3446.534	6.9	5.82	17.9	23.89	2423.01	5.3
S2(10)	5	11.92	14.4	2561.3	4.94	7.5	19.4	22.7	2658.3	5.146
S1(12)	9	11.14	15.7	2194.03	9	8.3	10.2	14.455	2189.91	8.29
S2(12)	5.5	4.86	8.2	1322.56	5.5	7.2	23.7	32.65	8652.11	6.9
S1(15)	11.03	11.3	13.4	9007.182	10.8	11.42	8.77	11.526	11478.89	11.1
S2(15)	7.7	6.98	11.6	7425.87	7.4	9.8	16.12	31.5	9620.72	9.4

Figures 19 to 24 depict the load-deflection curves for the concrete samples S1 (10), S2 (10), S1 (12), S2 (12), S1 (15), and S2 (15) after the repair process. These curves illustrate the relationship between the applied load and the resulting deflection of the repaired concrete samples. Moreover, Figures 25 to 30 present the load-strain curves for the same concrete samples after the repair. These curves illustrate the relationship between the applied load and the corresponding strain in the concrete samples following the repair process.

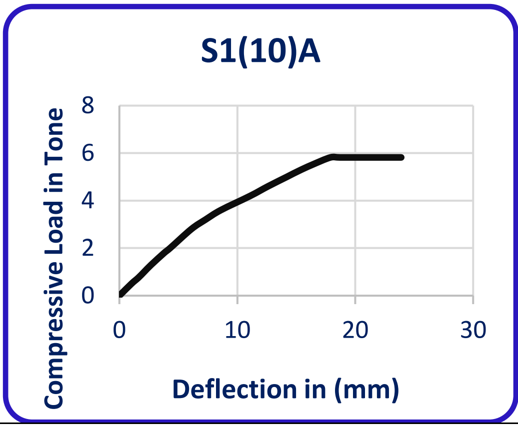

Figure 19 : The load-deflection curve for the concrete sample S1 (10)A after repair

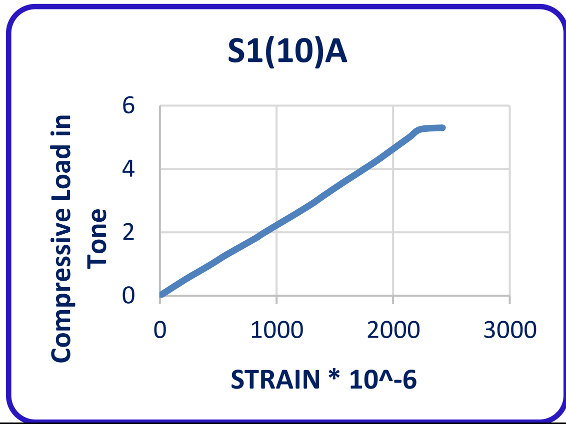

Figure 25 : The load-strain curve for the concrete sample S1 (10)A after repair

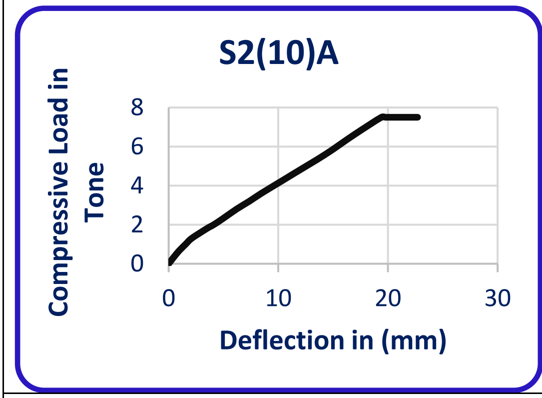

Figure 20 : The load-deflection curve for the concrete sample S2 (10)A after repair

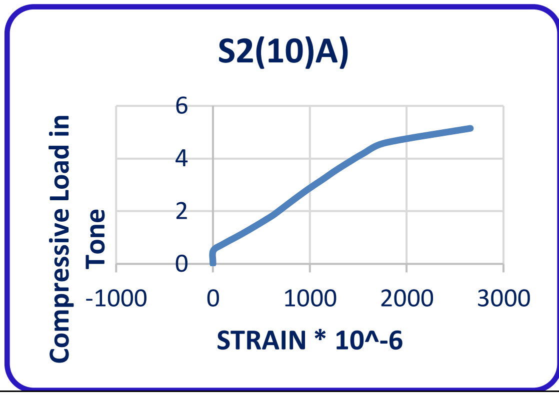

Figure 26 : The load-strain curve for the concrete sample S2 (10)A after repair

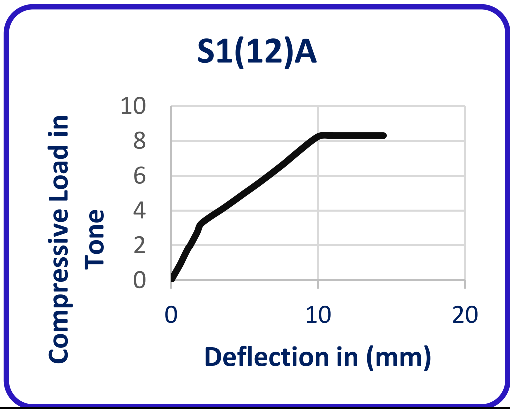

Figure 21 : The load-deflection curve for the concrete sample S1 (12)A after repair

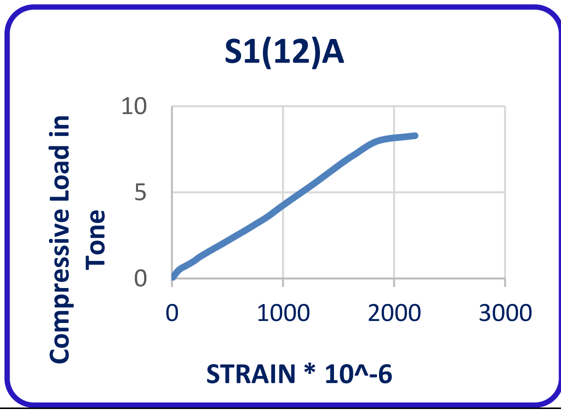

Figure 27 : The load-strain curve for the concrete sample S1 (12)A after repair

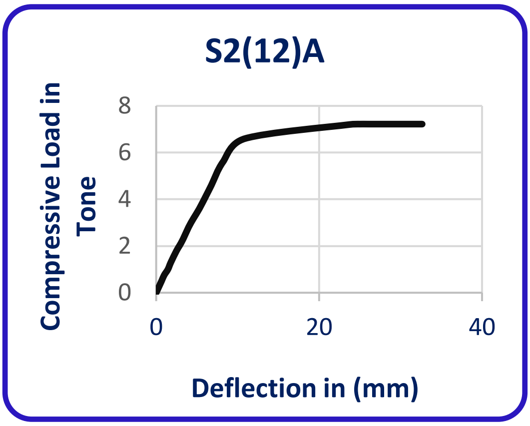	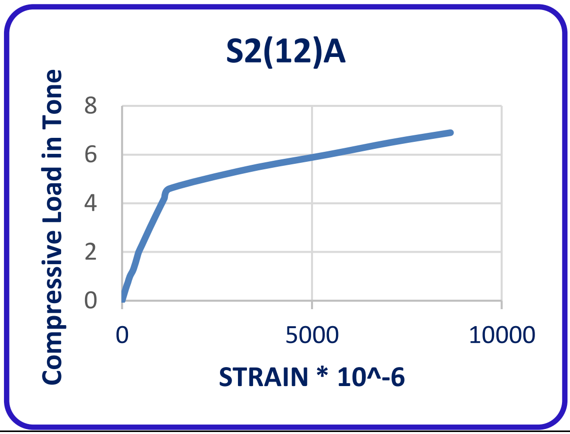
Figure 22 : The load-deflection curve for the concrete sample S2 (12)A after repair	Figure 28 : The load-strain curve for the concrete sample S2 (12)A after repair
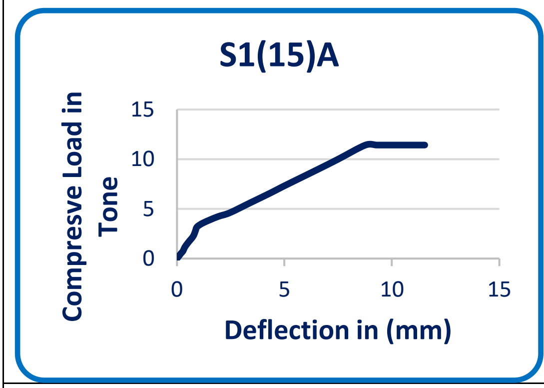	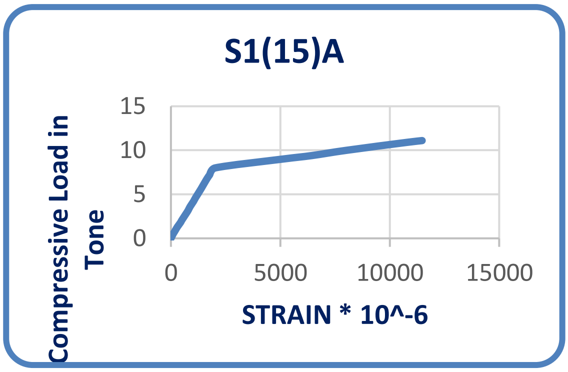
Figure 23 : The load-deflection curve for the concrete sample S1 (15)A after repair	Figure 29 : The load-strain curve for the concrete sample S1 (15)A after repair
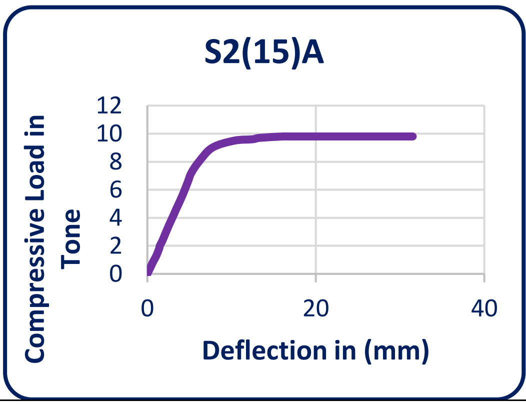	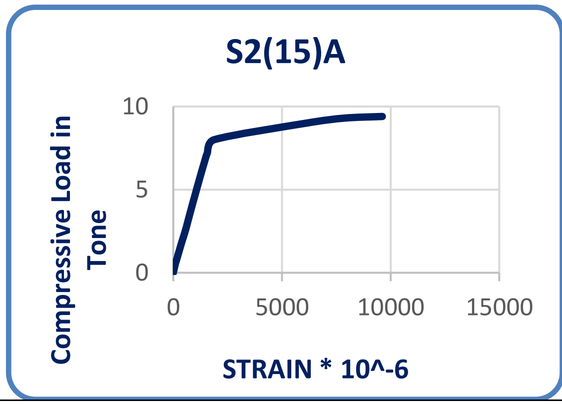
Figure 24 : The load-deflection curve for the concrete sample S2 (15)A after repair	Figure 30 : The load-strain curve for the concrete sample S2 (15)A after repair

Table 8 shows the maximum load for the control and other concrete samples before and after repair.

Table 8: Maximum load of control and concrete samples before and after repair

Maximum load (tons)		
S1(10)	control	7
	after repair	5.82
S2(10)	other sample	5
	after repair	7.5

Maximum load (tons)		
S1(12)	control	9
	after repair	8.3
S2(12)	other sample	5.5
	after repair	7.2

Maximum load (tons)		
S1(15)	control	11.03
	after repair	11.42
S2(15)	other sample	7.7
	after repair	9.8

Figures 31, 32 & 33 show the percentage of maximum load after repair and before repair for the control samples and the other concrete samples.

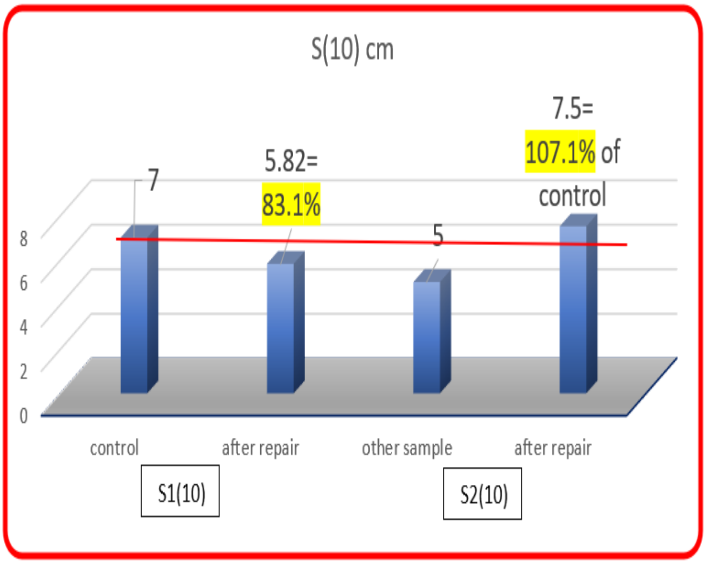

Figure 31: Comparison between maximum load for control and other concrete samples S (10) cm thickness before and after repair

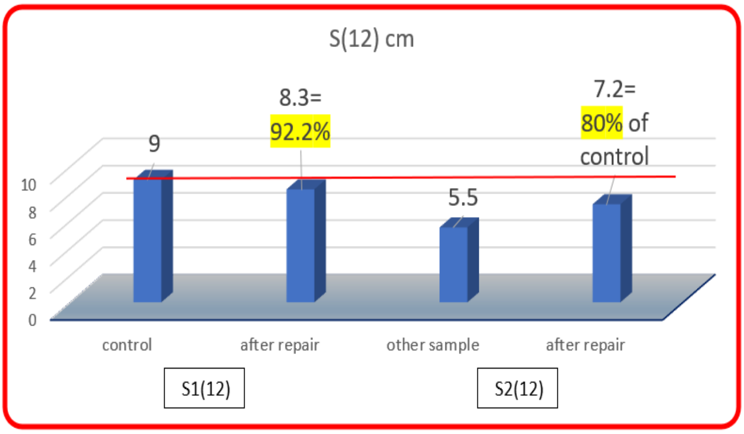

Figure 32: Comparison between maximum load for control and other concrete samples S (12) cm thickness before and after repair

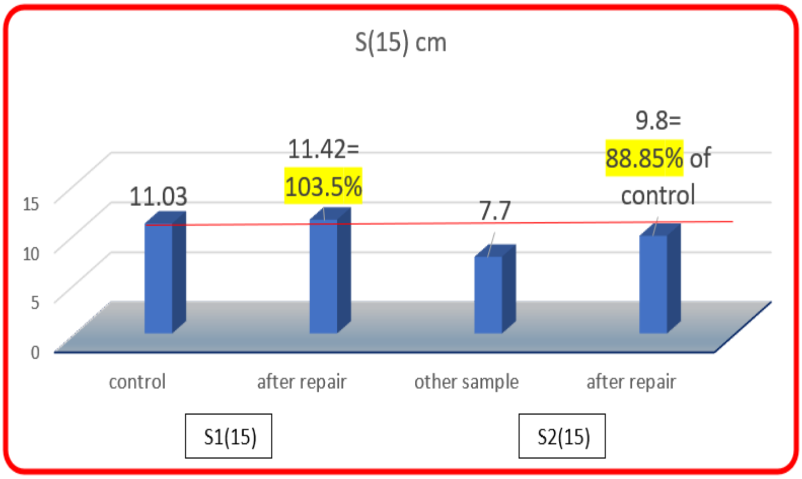

Figure 33: Comparison between maximum load for control and other concrete samples S (15) cm thickness before and after repair

The results of the study indicate that the repair methods employed produced excellent outcomes. The control samples, after undergoing repairs, demonstrated a maximum load capacity ranging from 83% to 103% compared to their original state. This suggests a significant improvement in the concrete samples' ability to bear loads. Similarly, the other concrete samples, which were subjected to 60% to 70% of the load applied to the control samples, exhibited substantial enhancements in their load-bearing capabilities.

Part 2: Blasting concrete samples

First step: Concrete samples exposed to initial blasting

Figure 34 shows the damage of the concrete samples after being exposed to the first blast.

Figure 34: The damage of the concrete samples after being exposed to the first blast

Second step: Concrete samples repaired and then exposed to a second blasting

Figure 35 shows the damage of the concrete samples after being repaired and exposed to a second blast.

Figure 35: The damage of the concrete samples after being repaired and exposed to a second blast

The results of the experiment show that, except for the 10 cm thick concrete sample which shattered during the first blast, the remaining samples demonstrated improved resistance to the second blast. Additionally, the findings indicate that concrete elements with greater thickness exhibit better resistance to blast loads compared to concrete elements with reduced thickness.

5. Conclusion and Recommendations

Conclusion

Based on the experimental work conducted, the following conclusions can be drawn regarding the effects of cement grout and epoxy compound in blast damage repair:

1. Concrete elements with greater thickness demonstrate better resistance to blast loads compared to those with reduced thickness.

2. When compared to similarly damaged and readily installable repair systems, cement grout materials such as Citorex grout offer a better flexural capacity and are hence a feasible alternative for blast damage restoration.

3. When compared to its similarly damaged and easily installable repair systems, epoxy compounds such as Kema epoxy 103 offer a better flexural capacity, making them a feasible solution for blast damage repair.

4. The suggested repair methods showed excellent results. For the control samples, the maximum load percentage was between (83-103) %, and this gives a good impression of the concrete sample's maximum load after the repairs were carried out on them. As for the other concrete samples, which were loaded by (60-70%) of the load of the control samples, the results also showed a good improvement in the sample's ability to bear the loads.

Recommendations

Therefore, it is recommended to continue monitoring and conduct additional tests to ensure the stability of the sample after repair. The effect of reduced maximum load on sample properties should be studied and measures taken to improve them. It is recommended to further evaluate the repair process and determine the cause of increased deformity after repair. We also recommend studying the effect of this increase in deformation on the strength and stability of the sample and taking the necessary measures to strengthen it.

Declarations

Availability of data and materials

Not applicable' in this section.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

The authors contributed only to provide information and review

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