EVALUATING THE STRUCTURAL BEHAVIOUR AND SUITABILITY OF SURFACE REPAIR MATERIAL USED FOR REPAIRING OF CONCRETE STRUCTURAL ELEMENTS.

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Introduction

Concrete structures undergo many structural and durability issues during their service life. To address this issue, this study endeavors to conduct a thorough assessment of the structural behavior and suitability of surface repair materials used for repairing concrete structures. The focus of the study is evaluation of shear bond strength between repair materials and concrete substrates by focusing on compressive strength tests, shrinkage tests and bond strength tests. This study aims to clarify how repair materials interact with concrete surfaces, revealing their compatibility and performance under different types of stress.

A key aspect of this study involves the analysis of stress development at different predetermined planes which includes angles of 30° and 45° to provide insights into the distribution of bond stress under loading. This approach enables a more comprehensive understanding of the shear bond strength characteristics of repair materials, facilitating informed decisions in selecting and optimizing repair strategies for concrete structures.

In essence, this study serves as a crucial step towards advancing the state-of-the-art in concrete repair technology, with implications extending beyond mere structural rehabilitation to encompass broader considerations of sustainability, safety, and resilience in the built environment.

Objectives

•This project aims to comprehensively evaluate the shear bond strength between repair materials and concrete substrates of conventional and commercial materials.

•The focus will be on conducting various tests to analyze the structural behavior to evaluate the bond strength and suitability of these repair materials for concrete surface repairs.

•This study focuses on the evaluation of the shear bond strength of substrate and repair material at different orientations of concrete structural elements.

Methodology and Materials used:

The materials employed in this study include Ordinary Portland Cement (OPC) for casting the substrate and commercially available products such as Styrene Butadiene Rubber (latex) emulsions from Sika and Asian Paints, and conventional cementitious materials, including Portland Pozzolana Cement (Blended Cement Mortar).

In this study, we employed a systematic methodology to investigate the structural behavior by conducting three different tests such as shrinkage test, compressive test, and bond strength test as a combination for substrate material and repair material.

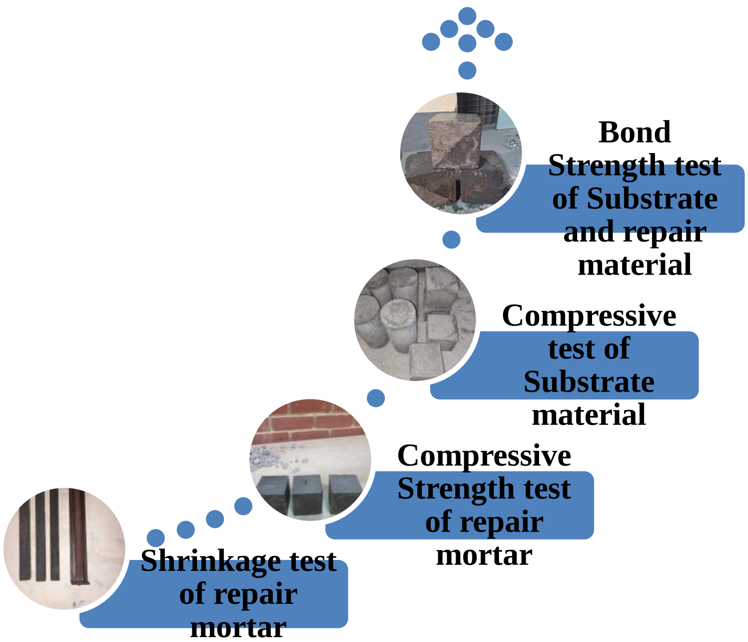

Fig.1 Methodology flow chart

Shrinkage test of repair material:

The shrinkage test for mortar serves to assess the potential for volume reduction or shrinkage in the material over time. In the context of Indian Standards (IS), such as IS 4031 Part 10 - 1988, the test helps ensure that mortar used in construction meets specific performance criteria

This test is crucial because excessive shrinkage in mortar can lead to cracks in structures, compromising their integrity. It allows for quality control in construction materials, ensuring that the mortar used is suitable for its intended purpose and can withstand the stresses associated with drying and setting.

Compressive Strength test of repair mortar:

The compressive strength test of cement mortar cubes as per IS 4031 Part 6-1988 involves determining the maximum load the cubes can withstand before failure occurs. It plays a pivotal role in verifying the suitability of the repair mortar to withstand expected loads and environmental conditions while meeting specified standards and requirements.

Bond strength test of combination of substrate and repair material:

One of the most common types of bonding tests is "Slant Shear Test" in which the interface is under combined state of compression and shear stresses. The procedure involves diagonally cutting a half section of hardened substrate at 30º and 45º from the horizontal and bonding it to new repair material, forming a complete cylinder or cube as **shown in fig 3.**

The presence of compressive stress enhances interface friction and interlocks, making it more influential than surface preparation, especially on smooth surfaces. The method applies compressive force to the substrate, strengthening the bond at the interface, utilizing principal stresses for this purpose. Understanding stress orientations is crucial. For instance, if a cube is cut at a 30° angle, it changes the orientation of the surfaces relative to the original stress axes. This modification affects how the stress is transmitted through the material, influencing its behavior under load.

Fig.2 Substrate cut an angle 30° and 45°

Fig.3 Combination of substrate with repair material

RESULTS AND DISCUSSIONS

Shrinkage test of Repair material:

Table 1 Tabular column for shrinkage test for 24 hours, and 72 hours

SI. No	Repair material	Original length of specimen (mm)	Length determined by comparator (mm)		Percentage Shrinkage	
			24 Hrs.	72 Hrs.	24 Hrs.	72 Hrs.
1	PPC (BM)	300	284.553	284.337	5.149%	5.221%
2	SBR (SLP)	300	284.871	284.832	5.043%	5.056%
3	SBR (AP)	300	284.562	284.516	5.146%	5.161%

In the shrinkage test, the original length of the specimen was 300 mm. After one day, the AP material exhibited a length reduction of 5.146%, increasing slightly to 5.161% after three days. The SLP material showed a length reduction of 5.043% after one day and 5.056% after three days, indicating the least shrinkage among the materials tested. In contrast, the BM material had a length reduction of 5.149% after one day, which increased to 5.221% after three days, reflecting the highest shrinkage. This comparison reveals that SLP had the lowest percentage reduction in volume, suggesting better dimensional stability over time. In contrast, BM showed the greatest shrinkage, indicating a higher tendency for volume reduction. AP showed moderate shrinkage values between SLP and BM. This data underscores the importance of selecting materials with minimal shrinkage to ensure durability and structural integrity in repair applications.

Compressive Strength test of Repair material:

The blended cement repair mortar demonstrated the highest compressive strength followed by the Asian Paints and the Sika polymer modified repair mortars. This suggests that the composition and formulation of the blended cement mortar contributed to its superior compressive strength compared to the other two types of mortar. The failure types observed provide insights into the behavior of each type of repair mortar under compressive stress. The presence of debonding in the Asian Paints repair mortar may indicate inadequate adhesion potentially affecting its overall performance. **Fig:4**. The occurrence of vertical cracks in the Sika repair mortar suggests that it might have experienced localized tensile stresses during compression, leading to crack formation**. Fig:5**. The observation of minor cracks in samples falling within the category of unsatisfactory failures indicates an abnormal or unacceptable level of cracking for cube samples, as shown in **Fig:6**. Satisfactory failure is characterized by cracking and failure of specimens at the peak applied load, with all four sides exposed with uniform cracks while the top and bottom faces remain undamaged or sustain only minor cracks**. Fig:6** representing unsatisfactory failure suggests that the specimen has developed more strength due to inadequate mix proportions, inconsistent particle sizes, and influences from the water-cement ratio.

The coefficient of variation reflects the variability or dispersion of compressive strength values within each set of samples. The lowest coefficient of variation was observed in the blended cement repair mortar indicating a relatively consistent performance across samples. In contrast, the Sika repair mortar exhibited a higher coefficient of variation suggesting greater variability in compressive strength among samples. The Asian Paints repair mortar fell in between the two. This variability could be attributed to factors such as material homogeneity, curing conditions, and testing methodologies.

Fig: 4 Debonding failure of Asian paints repair mortar

Fig: 5 Vertical failure of Sika latex power repair mortar

Fig: 6 Unsatisfactory failure of Blended mortar

Table:2 Compressive test results of repair materials for 7-days

Sl. No	Repair material	7-days Compressive Strength				
		Load (KN)	Strength (N/mm^2)	Avg. Strength (N/mm^2)	Standard Deviation	Co-efficient of variance (%)
1	SBR (AP)	30	6.02	7.022	1.003	14.286
2		35	7.02			
3		40	8.03			
1	SBR (SLP)	20	4.01	4.347	0.579	13.323
2		20	4.01			
3		25	5.02			
1	PPC (BM)	85	17.05	17.388	0.579	3.331
2		85	17.05			
3		90	18.06			

Area = 70.6X70.6mm

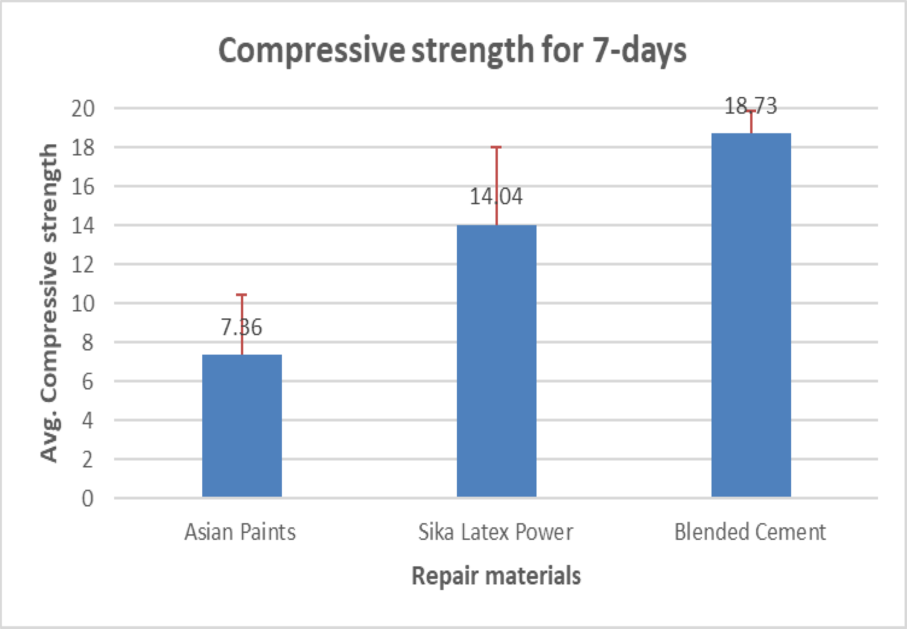

Fig: 7 Graph of Compressive strength VS repair materials for 7-days

Table: 3 Compressive test results of repair materials for 14-days

Sl. No	Repair material	14-days Compressive Strength				
		Load (KN)	Strength (N/mm^2)	Avg. Strength (N/mm^2)	Standard Deviation	Co-efficient of variance (%)
1	SBR (AP)	20	4.01	7.36	3.065	41.660
2		40	8.03			
3		50	10.03			
1	SBR (SLP)	90	18.06	14.04	4.013	28.571
2		50	10.03			
3		70	14.04			
1	PPC (BM)	90	18.06	18.73	1.158	6.186
2		90	18.06			
3		100	20.06			

Area = 70.6X70.6 mm

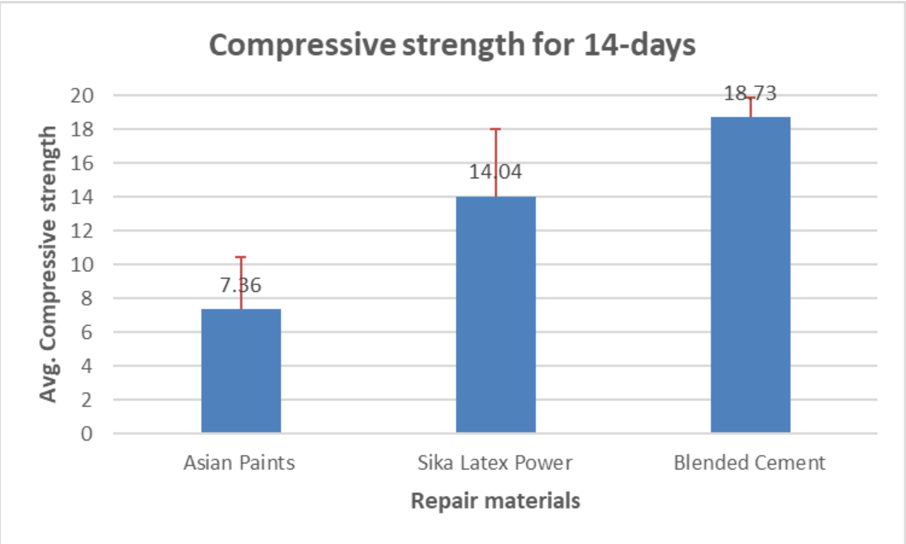

Fig: 8 Graph of Compressive strength VS repair materials for14-days

Compressive Strength test of Substrate material

Compressive Strength of concrete cubes and cylinders were conducted as per IS :516 2016. We employed M30 grade concrete with appropriate mix proportion as per IS:10262: 2019. Compressive strength is critical for evaluating the overall structural performance and durability of concrete. Higher compressive strength often correlates with better performance in resisting various types of loads, including shear. Although slant shear tests directly measure shear strength, this strength is influenced by the concrete's overall strength properties.

Fig: 9 Failure of substrate under compressive test

Table: 4 Compressive test results of Substrate materials for 28-days

SI. No	28-days Compressive Strength of substrate material									
	Load (KN)		Strength (N/mm^2)		Avg Strength (N/mm^2)		Standard Deviation		Co-efficient of variance (%)	
	Cube	Cylinder	Cube	Cylinder	Cube	Cylinder	Cube	Cylinder	Cube	Cylinder
1	670	310	29.778	17.551	28.519	18.684	1.480	1.498	5.188	8.017
2	605	360	26.889	20.382						
3	650	320	28.889	18.117						

Area of cube = 150X150 mm; Diameter of Cylinder = 150mm

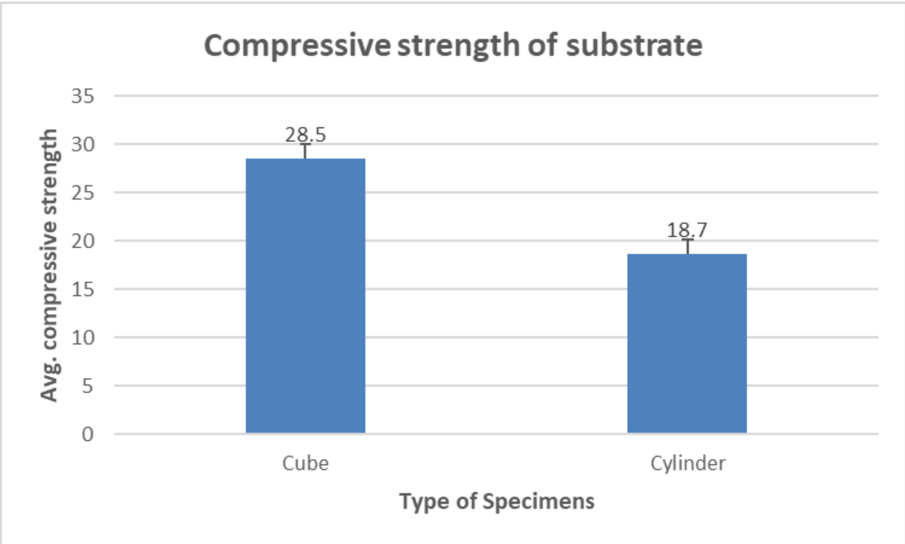

Fig: 10 Graph of Compressive strength of substrate materials

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Shear Bond Strength test:

The slant shear test as per the specification of ASTM C882 - 1999 was used to investigate the bond strength between OPC substrate and repair material.

The experimental slant shear strength test results are presented in the following tables**.** The failure modes for the slant shear specimens can be categorized into three types, Type A is the interfacial bond failure; Type B is the failure in the repair material; Type C is the substrate fracture.

	
Fig:11 Interfacial failure between substrate and Asian paints repair material at predetermined plane of 30°along with vertical cracks	Fig: 12 Failure in the Asian paints repair material bonded to substrate at predetermined plane of 30°
	

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Fig: 13 Substrate fracture and failure in the Asian paints repair mortar bonded to substrate at predetermined plane of 30°	Fig: 14 Failure in the Asian paints repair material of a specimen bonded to substrate at predetermined plane of 45°
	
Fig: 15 Interfacial failures between substrate and PPC repair material at a predetermined plane of 30° along with vertical cracks	Fig: 16 Substrate fracture and PPC repair material failure bonded to substrate at predetermined plane of 45°
	
Fig: 17 Substrate fracture and failure in the Sika repair mortar bonded to substrate at predetermined plane of 30°	Fig: 18 Substrate fracture and failure in the Sika repair mortar bonded to substrate at predetermined plane of 45°

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Fig: 19 Interfacial failures between substrate and Asian repair material at a predetermined plane of 30°

Fig: 20 Interfacial failures between substrate and Asian repair material at a predetermined plane of 45°

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Fig: 21 Failure in the sika repair material bonded to substrate at predetermined plane of 30°	Fig: 22 Failure in the sika repair bonded to substrate at predetermined plane of 45°
	
Fig: 23 Interfacial failures between substrate and PPC repair material at a predetermined plane 30°	Fig: 24 Failure in the PPC repair material bonded to substrate at predetermined plane of 45°

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Table: 5 Compressive strengths of cubes bonded with substrate and repair materials

SI. No	Composite specimen	Failure load for Predetermined angle (KN)		Compressive strength of the specimen = P/ A_0 in MPa							
		Cube		30°				Cube 45°			
		30°	45°	CS	Avg. CS	SD	CV	CS	Avg. CS	SD	CV
1	SBR (AP)	260	290	11.56	10.96	1.43	13.03	12.89	12.00	1.94	16.14
2		210	300	9.33				13.33			
3		270	220	12.00				9.78			
1	SBR (SLP)	390	380	17.33	16.67	0.97	5.81	16.89	16.74	0.26	1.53
2		350	380	15.56				16.89			
3		385	370	17.11				16.44			
1	PPC (BM)	220	240	9.78	12.59	3.78	30.02	10.67	10.52	1.12	10.63
2		250	260	11.11				11.56			
3		380	210	16.89				9.33			

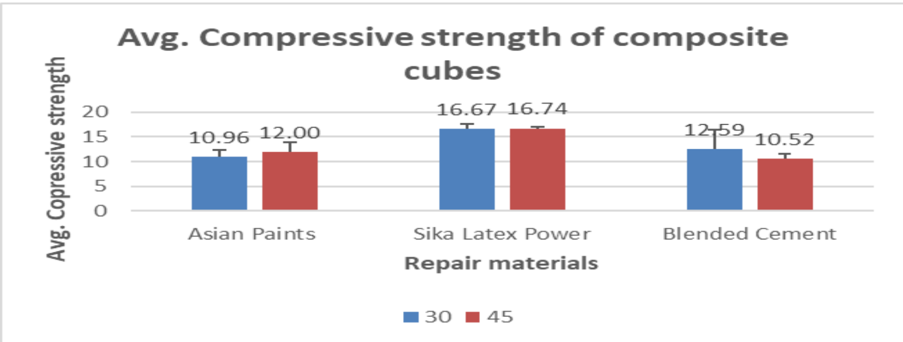

Fig:25 Graphical representation of Avg. compressive strength of composite cubes

The compressive strength of the specimen is determined using the formula **P/A_0**

Where, P is the load at failure in N/mm².

A_0 is the surface area of the cube and cylinder (mm²).

According to **Table 3.5,** for AP repair mortar bonded to an OPC substrate cube at an orientation of 30°, the strength was 10.96 N/mm². In contrast, at a 45° orientation, the compressive strength increased to 12 N/mm², indicating that a higher equilibrium was maintained at 45°. Similarly, for SLP, the strength was also higher at 45° with a value of 16.74 N/mm². In the case of BM, the 30° orientation exhibited a higher strength of 12.59 N/mm² compared to the 45° orientation, which had a strength of 10.52 N/mm². Overall, in comparison with conventional and commercial repair materials, the commercial repair material SLP bonded to the substrate demonstrated the highest strength.

Table: 6 Compressive strengths of cylinders bonded with substrate and repair materials

SI. No	Composite specimen	Failure load for Predetermined angle (KN)		Compressive strength of the specimen = P/ A_0 in MPa							
		Cylinder		30°				45°			
		30°	45°	CS	Avg. CS	SD	CV	CS	Avg. CS	SD	CV
1	SBR (AP)	6	5	0.34	0.91	0.49	54.49	0.28	0.34	0.06	16.67
2		20	6	1.13				0.34			
3		22	7	1.24				0.40			
1	SBR (SLP)	16	15	0.91	1.24	0.32	25.31	0.85	1.17	0.28	23.87
2		23	24	1.30				1.36			
3		27	23	1.53				1.30			
1	PPC (BM)	9	11	0.51	0.53	0.03	6.19	0.62	0.66	0.07	9.90
2		10	13	0.57				0.74			
3		9	11	0.51				0.62			

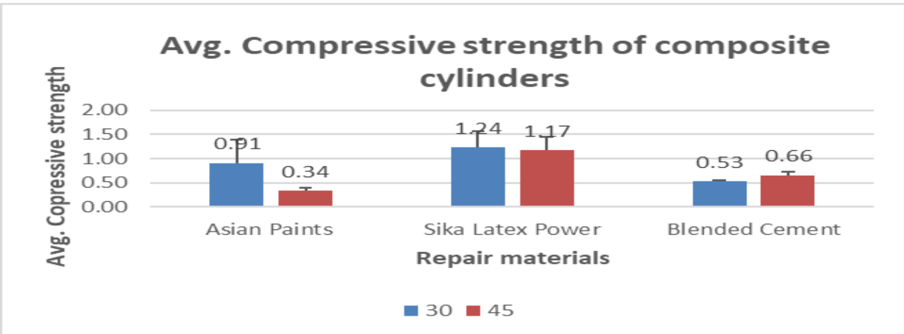

Fig: 26 Graphical representation of Avg. compressive strength of composite cylinders

In the analysis of cylinders oriented at planes of 30° and 45°, it was observed that the load at failure was significantly lower compared to that of cubes. This reduction in strength is attributed to the smooth finish of the cylinder surfaces as **shown in fig.20** and **fig. 24,** before bonding to the substrate at various orientations. For AP, the compressive strength was 0.91 N/mm² at 30° and decreased to 0.34 N/mm² at 45°. In the case of SLP, the compressive strength was higher, with values of 1.24 N/mm² at 30° and 1.17 N/mm² at 45°. BM exhibited compressive strengths of 0.53 N/mm² at 30° and 0.66 N/mm² at 45°. These results indicate that the surface finish and orientation significantly influence the compressive strength, with smoother surfaces leading to reduced bonding efficacy and lower overall strength in cylinders compared to cubes.

Normal stresses on an inclined plane can be determined using the formula, $\boldsymbol{\sigma = P\cos\theta / A_i}$

Shear or tangential stress on an inclined plane is calculated using the formula $\boldsymbol{\tau = P\sin\theta / A_i}$

where: σ is the normal stress on the inclined plane (N/mm²); P is the load at failure (N). θ is the orientation of the plane (degrees); A_i is the area of the inclined surface (mm²). τ represents the shear stress in N/mm².

This formula emphasizes the role of the load angle and surface area in determining the distribution of shear stresses when a load is applied, providing essential insights into the material's shear strength characteristics under various conditions.

In both cubes and cylinders oriented at 30° and 45°, the SLP repair material bonded to the substrate recorded the highest normal stresses. Specifically, for cubes at a 30° orientation, the normal stress reached 12.50 N/mm², while for cylinders at the same orientation, the normal stress was 0.93 N/mm² referring to the **table 5.**

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Table: 7 Normal stresses of cubes on inclined plane at predetermined plane.

Sl. No	Composite specimen	Failure load for Predetermined angle (KN)		Normal Stresses on Inclined plane at predetermined Plane=P cos θ / A_i in MPa							
		Cube		30°				45°			
		30°	45°	NS	Avg	Sd	CV	NS	Avg	Sd	CV
1	SBR (AP)	260	290	8.67	8.22	1.07	13.03	6.44	6.00	0.97	16.14
2		210	300	7.00				6.67			
3		270	220	9.00				4.89			
1	SBR (SLP)	390	380	13.00	12.50	0.73	5.81	8.44	8.37	0.13	1.53
2		350	380	11.67				8.44			
3		385	370	12.83				8.22			
1	PPC (BM)	220	240	7.33	9.44	2.83	30.02	5.33	5.26	0.56	10.63
2		250	260	8.33				5.78			
3		380	210	12.67				4.67			

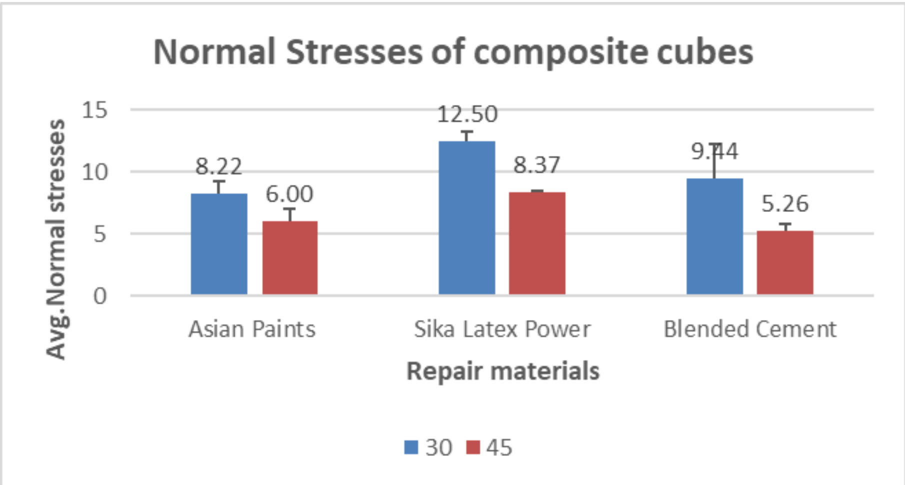

Fig: 27 Graphical representations of Avg. Normal stresses of composite cubes

Table: 8 Normal stresses of cylinders on inclined plane at predetermined plane.

SI. No	Composite specimen	Failure load for Predetermined angle (KN)		Normal Stresses on Inclined plane at predetermined Plane=P cos θ / A_i in MPa							
		Cylinder		30°				45°			
		30°	45°	NS	Avg	Sd	CV	NS	Avg	Sd	CV
1	SBR (AP)	6	5	0.25	0.68	0.37	54.49	0.14	0.17	0.03	16.67
2		20	6	0.85				0.17			
3		22	7	0.93				0.20			
1	SBR (SLP)	16	15	0.68	0.93	0.24	25.31	0.42	0.58	0.14	23.87
2		23	24	0.98				0.68			
3		27	23	1.15				0.65			
1	PPC (BM)	9	11	0.38	0.40	0.02	6.19	0.31	0.33	0.03	9.90
2		10	13	0.42				0.37			
3		9	11	0.38				0.31			

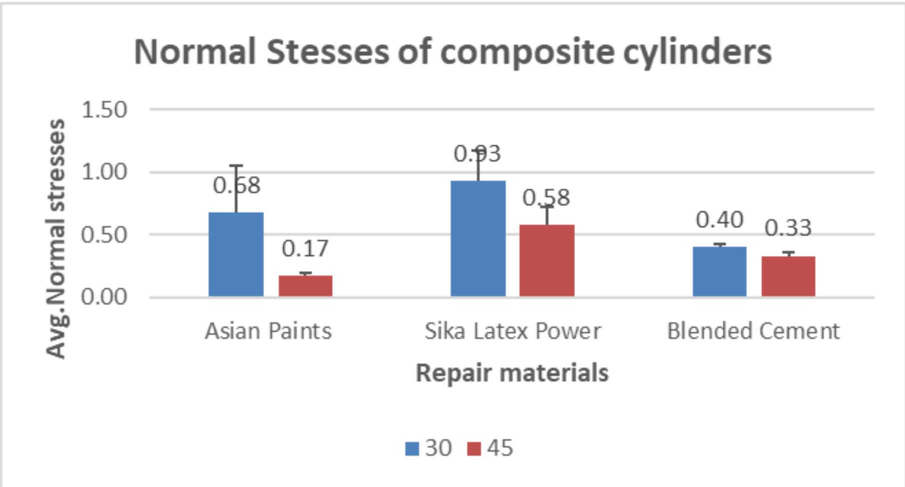

Fig: 28 Graphical representations of Avg. Normal stresses of composite cylinders

Table: 9 Shear stresses of cubes on inclined plane at predetermined plane.

SI. No	Composite specimen	Failure load for Predetermined angle (KN)		Shear Stresses on Inclined plane at predetermined plane, τ = Psin θ / A_i in MPa							
		Cube		30°				45°			
		30°	45°	SS	Avg	Sd	CV	NS	Avg	Sd	CV
1	SBR (AP)	260	290	5.00	4.75	0.62	13.03	6.44	6.00	0.97	16.14
2		210	300	4.04				6.67			
3		270	220	5.20				4.89			
1	SBR (SLP)	390	380	7.51	7.22	0.42	5.81	8.44	8.37	0.13	1.53
2		350	380	6.74				8.44			
3		385	370	7.41				8.22			
1	PPC (BM)	220	240	4.23	5.45	1.64	30.02	5.33	5.26	0.56	10.63
2		250	260	4.81				5.78			
3		380	210	7.31				4.67			

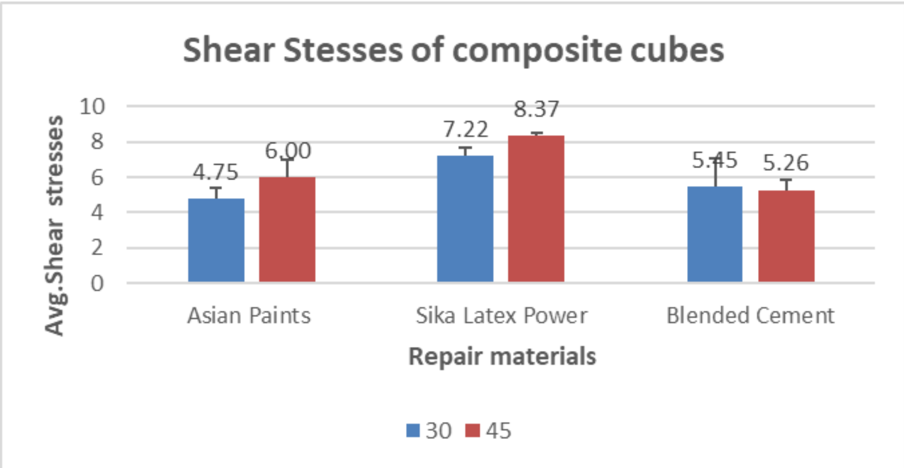

Fig: 29 Graphical representation of Avg. shear stresses of composite cubes

Table:10 Shear stresses of cylinders on inclined plane at predetermined plane.

SI. No	Composite specimen	Failure load for Predetermined angle (KN)		Shear Stresses on Inclined plane at predetermined plane, $\tau = P\sin\theta / A_i$ in MPa							
		Cylinder		30°				45°			
		30°	45°	SS	Avg	Sd	CV	NS	Avg	Sd	CV
1	SBR (AP)	6	5	0.15				0.14	0.17	0.03	16.67
2		20	6	0.49	0.39	0.21	54.49	0.17			
3		22	7	0.54				0.20			
1	SBR (SLP)	16	15	0.39	0.54	0.14	25.31	0.42	0.58	0.14	23.87
2		23	24	0.56				0.68			
3		27	23	0.66				0.65			
1	PPC (BM)	9	11	0.22	0.23	0.01	6.19	0.31	0.33	0.03	9.90
2		10	13	0.25				0.37			
3		9	11	0.22				0.31			

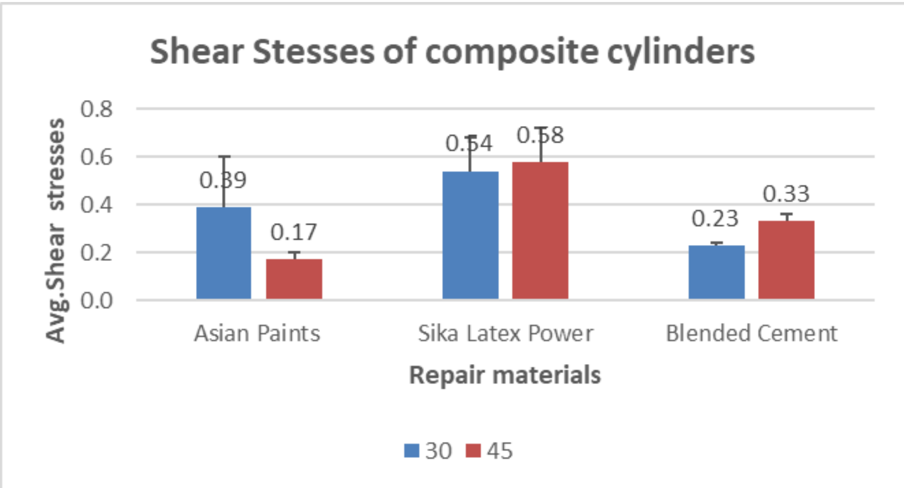

Fig: 30 Graphical representation of Avg. shear stresses of composite cubes

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At a 30° orientation in AP bonded to substrate concrete, the normal stress is significantly higher at 8.22 N/mm² compared to the shear stress of 4.75 N/mm². This indicates that tensile or compressive stresses (normal stresses) are more critical at the bonded interface than shear stresses.

The higher normal stress value suggests that the adhesion between the concrete and the repair material is strong in shear, effectively transferring loads without sliding or delamination.

However, the observed failure in the specimen in **Fig:11,** which includes cracks in both the repair material and the substrate, indicates a failure under high normal stresses. Despite the strong shear adhesion, the high normal stresses lead to tensile or compressive failures. Addressing issues such as material compatibility, surface preparation, and structural defects is essential to mitigate stress concentrations and prevent crack formation, ensuring the long-term durability and performance of repaired structures.

In the case of SLP at a 30° inclination, the observed normal stress of 12.50 N/mm² surpasses the shear stress value of 7.22 N/mm². This suggests that compressive stresses are more significant than shear stresses at the interface. The predominant failure pattern, characterized by interfacial failure with vertical cracks throughout the specimen, underscores the critical role of normal stresses in determining the structural integrity. The occurrence of vertical cracks from **Fig: 17** indicates that the applied loads induced tensile stresses exceeding the material's capacity, leading to failure primarily along the interface between the repair material and the substrate.

In the case of the conventional blended mortar repair material bonded to the substrate at a 30° orientation, the observed normal stress of 9.44 N/mm² exceeds the shear stress value of 5.45 N/mm². This disparity suggests that tensile stresses play a more significant role than shear stresses at the interface. The occurrence of failure specifically at the interface of the predetermined angle of 30° from **Fig: 15** indicates that the stresses acting along this angle exceed the material's capacity, resulting in failure primarily at the interface between the repair material and the substrate.

At a 45° orientation in AP bonded to substrate, failure occurred in the repair material with both normal and shear stresses measured at 6 N/mm². This scenario suggests a balanced distribution of stresses, with neither normal nor shear stresses significantly dominating the failure mechanism. From **Fig: 12** the occurrence of failure within the repair material itself, rather than at the interface with the substrate, indicates that the stresses within the repair material exceeded its capacity, leading to material failure. This balanced failure mode suggests that both tensile/compressive and shear stresses contribute to the overall failure mechanism. To prevent such failures, it's crucial to ensure the repair material's compatibility with the substrate.

At a 45° orientation, the SLP repair material bonded to the substrate exhibited both normal and shear stresses of 8.37 N/mm^2. The occurrence of failure within the repair material and the substrate surface, accompanied by vertical cracks, suggests a critical combination of stresses acting on the system. From **Fig: 18** the presence of vertical cracks indicates that the applied stresses exceeded the material's capacity, leading to failure primarily within the repair material and the substrate surface. The equal magnitude of normal and shear stresses suggests that both types of stresses contributed significantly to the failure mechanism.

At a 45° orientation in BM bonded to the substrate, failure occurred in both the repair material and the substrate surface with observed normal and shear stresses of 5.26 N/mm^2. From **Fig:16** this indicates that both normal and shear stresses were significant contributors to the failure. The equal values of normal and shear stresses imply that the interface and the materials themselves were equally stressed, leading to a failure that is not solely interfacial but also within the materials. This highlights the need for improving the mechanical properties and bonding efficacy of the repair material to enhance overall structural integrity under combined stress conditions.

In the case of cylinders, the failure load was significantly lower compared to that of cubes due to the smooth finish of the surface to be bonded to the substrate. This smooth finish resulted in very low values of both shear and normal stresses. Despite these low values, normal stress consistently exceeded shear stress at both 30° and 45° inclinations. The failure predominantly occurred at the interface between the repair material and the substrate. This suggests that the smooth surface finish adversely affected the bond strength, leading to weak adhesion and making the interface the primary failure point. It highlights the critical importance of surface roughness in enhancing the bond strength and overall durability of the repair. Ensuring adequate surface preparation to increase roughness can improve adhesion and help distribute stresses more effectively.

Overall, SLP exhibited higher normal stress compared to both the conventional

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material BM and the commercial material AP in the cases of both cylinders and cubes at different orientations. In all instances, the normal stress was greater than the shear stress. This superior performance of SLP underscores its effective load-bearing capacity and adhesion properties. The critical role of surface preparation, specifically the use of a rough surface with slight undulations, was evident in enhancing the bond strength and stress distribution. The rough surface increases the mechanical interlocking between the repair material and the substrate, this finding emphasizes the importance of surface preparation in achieving optimal performance of repair materials under various stress conditions.

CONCLUSIONS

- Surface Preparation: Smooth surface finishes of the substrate resulted in significantly lower bond strength, highlighting the necessity of adequate surface preparation to increase roughness and enhance the bond. The use of rough surfaces with slight undulations proved beneficial in increasing the mechanical interlocking between the repair material and the substrate, leading to better performance under load.
- Compressive Strength: Blended cement repair mortar exhibited the highest compressive strength, followed by the Asian Paints and Sika polymer-modified repair mortars. The variability in compressive strength, as indicated by the coefficient of variation, was lowest for the blended cement repair mortar, suggesting consistent performance.
- Shear Bond Strength: The slant shear test results revealed that the commercial repair material Sika polymer (SLP) demonstrated the highest bond strength to the substrate compared to both conventional blended mortar (BM) and Asian Paints (AP) repair materials. The bond strength was significantly influenced by the surface preparation of the substrate, with rough surfaces providing better mechanical interlocking and thus higher bond strength.
- Stresses: Normal stresses were consistently higher than shear stresses across different orientations and types of repair materials. This finding underscores the importance of ensuring strong adhesion to handle tensile and compressive stresses effectively. The failure patterns indicated that compressive failures were more critical at the interface than shear failures. This emphasizes the need to focus on

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the repair material's compatibility and surface preparation to improve adhesion and overall structural integrity.

Future Studies:

The future scope of evaluating the structural behavior and suitability of surface repair materials for concrete structural elements, particularly through bond strength tests at various angles, is extensive and promising. Expanding the range of testing angles can provide a more comprehensive understanding of shear bond strength and stress which is crucial for optimizing repair techniques. Advanced material characterization, focusing on both high-performance and sustainable materials, can lead to the development of repair solutions with superior bond strength, reduced shrinkage, and lower carbon emissions. Assessing the durability and compatibility between new repair materials and existing concrete structures is essential to ensure long-term performance and structural integrity. Finally, educational initiatives through publications and conferences can raise awareness and encourage the adoption of these advancements in the construction industry, ultimately contributing to sustainability goals.

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