Journal of Manufacturing Engineering, June 2025, Vol. 20, Issue. 2, pp 067-075
DOI: https://doi.org/10.37255/jme.v20i2pp067-075

CRACK FORMATION AND CONTROL STRATEGIES IN CONCRETE SYSTEMS

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Abstract

Concrete cracks in buildings are a common and routine occurrence that occurs in civil engineering, regardless of the nature and size of the work. It is almost unavoidable due to the nature of concrete material, i.e., its weak tensile strength, and for several environmental and structural reasons. The cracks not only deteriorate the aesthetic finish and appearance of the buildings but, above all, compromise their mechanical stability, safety, and life. They result in the weakening of major structural members such as slabs, beams, and columns, and thus destabilise the building. Concrete cracking is initiated by a number of causes, such as construction defects, defects in design, poor-quality materials, defective curing, and environmental factors such as variations in temperature, shrinkage, or chemical reaction. Engineers and scientists have been working hard over the past couple of years with the aim of understanding the crack initiation and propagation, with the aim of utilising appropriate preventive and corrective action. Detection and structural vs. non-structural differentiation of cracks are now possible, as the majority of them are obligated to carry out the right type of repair jobs. Their ability to repair is a factor of knowing the right repair method and material, depending on the width, direction, location, and level of the crack. There are cracks that are surface minor imperfections and others that are inherent flaws that require treatment with some level of urgency. This paper aims to induce cracking in concrete structures, i.e., causes, nature, and effects of some patterns of cracking in general. It also provides prevention strategies and remedial techniques, i.e., chemical injection, control joints, reinforcement, and advanced repairs such as epoxy injection, stitch cracking, and dry packing. Proper practice during construction and vigilant observation of structures have been stressed. They are significant steps in averting further increases in cracks. In short words, understanding causative causes of crack initiation and respective remedies can go a long way in the durability, safety, and performance of concrete structures over their required period.

Keywords: *Cracks, causes, remedial measures, preventive techniques.*

1. Introduction

The most common engineering material used in construction is concrete, since it is more affordable than other building materials and has superior strength and durability compared to other building materials. Concrete's limited tensile strength is one of its main disadvantages, however. Because of this disadvantage, concrete is more likely to develop and grow microcracks, which can reduce the material's overall strength and longevity. Tensile stresses caused by things like direct tensile loading, plastic shrinkage, or expansive chemical reactions are frequently the origin of these cracks. Because of this, concrete works well under compression but adversely under tension, which may ultimately result in problems with structural integrity if reinforcement or other efforts to increase the material's resistance to tensile forces aren't taken [1]. In the middle of the 19th century, concrete structures began to be utilised. However, the development and adoption of concrete construction developed slowly because of the low quality of cement and the lack of innovations in technology at the time. [2]. Cracks are a big problem in concrete construction. They mess up how a building looks and weaken its walls, making it less safe and durable. Cracks can form because the concrete gets worn out, the metal inside rusts, or because of mistakes during construction. Changes in temperature and concrete shrinking can also cause cracks. By the end of the 19th century, concrete was rapidly advancing thanks to improvements in manufacturing, experimental work, computational techniques, and production methods. Today, it stands as one of the most often used materials in modern construction. As concrete ages, cracks can lead to leaks and allow moisture, oxygen, chemicals, and gases to infiltrate, causing significant degradation and corrosion. Cracks serve as early warnings of potential structural failure. While some cracking is normal, excessive cracking can be concerning. Durability issues in concrete necessitate rehabilitation strategies and materials to

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maintain structural integrity and longevity. Repairing cracks is essential for preventative maintenance, helping to prolong the service life of structures by preventing the ingress of water and harmful substances that can lead to corrosion and other damaging effects on concrete [3].

2. Literature review

Syed Mohd Mehndi et al. [4] explore the causes and evaluation of cracks in reinforced concrete structures, emphasising the importance of understanding crack origins for effective repair. They note that cracks can occur in both the plastic and elastic states of concrete, and different repair techniques are required depending on the type and location of the cracks. The study highlights various methods for crack evaluation, including the use of Crack Compactors, ultrasonic testing, and photographic examination. The authors argue that proper diagnosis is crucial for the longevity of repairs and the overall integrity of structures. Grishma Thagunna's research [5] investigates the causes of building cracks and their repair. It illustrates that although cracks cannot be prevented, they may be controlled with the right equipment, methods, and designs. The study highlights the need to identify and address fractures early on by distinguishing between those that are harmless and those that have the potential to weaken a structure. It also outlines various methods for discovering cracks. The study ultimately comes to the conclusion that while cracks cannot be prevented, they can be minimised, and the most efficient repair techniques should be selected following an extensive assessment of the fractures. Kishore Kunal, Namesh Killemsetty (2014) [6] discuss the importance of visually monitoring buildings to identify and manage structural cracks. The secret to successfully fixing these cracks is knowing what causes them. Along with the structure's history and specifications, the research offers engineers a comprehensive checklist to analyse several crack characteristics, including location, shape, size, depth, and behaviour. Cracks can be classified and diagnosed with the use of careful data collection and monitoring, allowing for the implementation of suitable repairs and preventative measures. When evaluating cracks, it also highlights the importance of taking environmental elements like soil conditions and water exposure into account. While cracks cannot be prevented, their consequences can be minimised by taking proactive measures during construction. Aruya et al. [7] discuss the causes of cracks in concrete structures and the corresponding repair methods. Buildings are frequently experiencing cracking, which often shows up as defects over time or as a result of poor construction practices. These cracks could be a sign of more serious problems or underlying damage that compromises durability, structural integrity, or aesthetics. There are two categories of cracks: structural and non-structural. A building's safety may be compromised by structural cracks, which can be brought on by issues including overloading, poor materials, bad construction methods, and design errors. In contrast, non-structural cracks are caused by factors like chemical reactions, material shrinkage, changes in temperature, or corrosion of reinforcement and typically impact use or appearance rather than safety. Cracks cannot be completely avoided; however, their effects can be decreased. Managing cracks and preserving a structure's life requires careful material selection, good construction practices, and the application of suitable repair techniques. By following these guidelines, you can reduce the chances of cracking and preserve the building's durability and strength over time. Barve et al. [8] discuss the common occurrence of the causes of building fractures, both structural and non-structural. They emphasise that understanding the causes of cracks helps engineers implement effective repairs. Structural cracks, caused by incorrect design, faulty construction, or overloading, can compromise safety, while non-structural cracks result from factors such as moisture, thermal fluctuations, or foundation issues. In their case study, they observed that most cracks originated from corners of openings or joints, with none exceeding 10mm in depth, indicating plaster cracks. Probable causes include material non-uniformity, construction speed, and insufficient curing. Non-destructive testing is recommended for a more accurate assessment. Das et al. [9] discuss the growing challenge engineers face in addressing cracks in building structures, specifically in the CCEM building. Structures will unavoidably crack, although designers work hard to mitigate many of the causes and incorporate tolerances for others. While structural safety is a top priority, they emphasise that various types of cracks in both structural and non-structural parts can result from a number of sources, including building faults and uncontrollable situations. It is crucial to identify problems early and take preventive action. The study emphasises the fact that various cracking types and locations require different repair materials and methods, with certain cracks posing major structural hazards. These problems can be reduced by using proper construction materials and methods and by managing the primary causes of cracks as soon as possible.

3. Classification of cracks

Cracks in buildings happen a lot. They usually occur when something in the building is under too much pressure. This pressure can come from different things

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like heavy objects, wind, earthquakes, or even fixing the foundation. Sometimes, it's also because of temperature changes, vibrations, humidity, or chemicals.

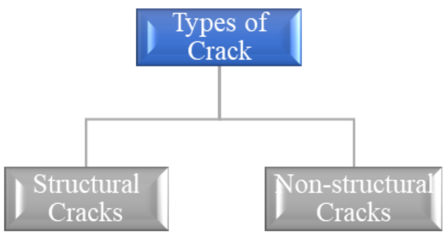

Fig. 1 Classification of cracks

Based on the width crack classification

Figure 1 shows the classification of cracks based on their width, which is essential for structural assessment and determining the severity and appropriate remedial action. Crack classification based on width is a crucial aspect of structural assessment in civil engineering, as it helps determine the severity of the crack and the required remedial actions.

Table 1- Based on the width crack classification

Classification	Width
Hairline Cracks	< 0.1 mm
Fine Cracks	0.1 mm to 0.3 mm
Medium Cracks	0.3 mm to 1.0 mm
Wide Cracks	1.0 mm to 5.0 mm

3.1 Structural cracks

Errors in construction, design, or placing excessive weight on a building can all result in structural cracks [9]. These cracks can put the building's safety at risk and often happen in important parts like beams, columns, and slabs.

3.2 Flexural Cracks

In reinforced concrete structures exposed to bending stresses, a specific type of crack known as a flexural crack [10]. The cracks typically start in the member's tensile zone, such as a beam's bottom surface under downward stress, and spread perpendicular to the axis of bending. They are frequently evenly distributed throughout the areas of the structure that are subjected to the highest loads, such as near mid-span areas in beams. Figure 2 illustrates flexural cracks typically observed in reinforced concrete beams under bending stresses, often starting from the tensile zone and progressing perpendicular to the axis of bending.

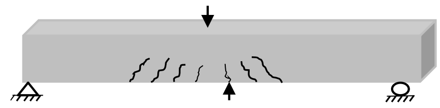

Fig. 2- Flexural Cracks [11]

Shear Cracks

Shear cracks, which often appear as diagonal cracks in beams, slabs, or columns, are structural failures caused by high shear stress [12]. When internal shear forces, which might be caused by things like insufficient strengthening, significant loads, or seismic activity, exceed the material's shear strength, cracks form. Shear cracks have the potential to cause slow structural damage if not addressed. Figure 3 presents shear cracks, which are diagonal cracks formed in structural elements like beams due to excessive shear stress.

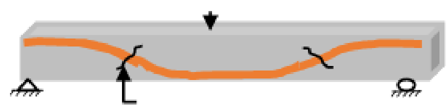

Fig. 3 Shear cracks [11]

3.3 Non-structural cracks

Non-structural cracks are typically superficial and create minor cracking that doesn't affect the structural integrity of a material or building. These cracks result from fluctuations in moisture levels, thermal expansion, temperature changes, surface crazing, and the influence of gases and liquids [1, 9].

3.4 Elastic Deformation

Material strain occurs when subjected to stress, particularly when two materials with differing properties are combined. At the junction where these materials meet, varying shear stresses develop due to their distinct behaviours. The primary causes of elastic deformation in a building's structural components are dead load and live load. These loads lead to deformation as the materials respond to the stresses placed upon them, with differing reactions at the points where they are joined, leading to strain and potential structural impacts over time [13].

Remedial Measures of Elastic Deformation

- Install slip joints beneath the concrete slab where it meets the walls.
- Use materials with suitable elastic properties for the intended load.
- Incorporate joints that move horizontally between the reinforced concrete beam or slab and the top of the brick panel.

3.5 Shrinkage

When most buildings retrieve moisture from the air, they expand, and when they dry out, they shrink or contract [4]. Shrinkage occurs in two forms: plastic shrinkage and drying shrinkage.

3.6 Plastic Shrinkage Cracking

These cracks form when water evaporates from the fresh concrete's top layer and rises more quickly than the bleed water from the concrete underneath, causing the surface concrete to shrink. As the concrete beneath tries to resist this shrinkage, tensile stresses develop in the still-soft concrete. Consequently, shallow cracks of varying depths, 5cm to 10cm deep, and up to 3mm wide. These cracks are typically parallel, spaced 0.3 to 1 meter apart. Initially narrow, these cracks may deepen over time, becoming full-depth fissures. Plastic shrinkage cracking occurs when the temperature of the air above the concrete is high. Figure 4 depicts plastic shrinkage cracks that occur when water evaporates from the surface of fresh concrete faster than it can be replenished by bleed water.

Fig. 4- Plastic shrinkage crack

Remedial Measures of Plastic Shrinkage Cracking

- Styrene butadiene latex co-polymer as a bonding agent: A chemical used to help materials stick together.
- Fog nozzles: Tools that create a fine mist to keep the air above concrete moist.
- Plastic sheeting: Covers are placed over concrete to protect it.
- Windbreaks: Barriers set up to reduce wind speed around concrete.

3.7 Drying Shrinkage Cracking

After hardening, concrete dries and shrinks as excess water evaporates**.** If this shrinkage is stopped by reinforcement bars, it can cause cracks called plastic shrinkage cracks. Tension develops in the structure because of the combination of shrinkage and resistance from other parts of the structure. Since concrete isn't good at handling tension, cracks start to form when the tension exceeds its strength. These cracks start on the surface and can get deeper over time. The type of rocks used in the concrete and the water-to-cement ratio affect how much it shrinks. Smaller aggregate and finer gel lead to more shrinkage. Putting in contraction joints and reinforcing the concrete properly can help prevent shrinkage cracks. Figure 5 shows drying shrinkage cracks that appear as concrete loses moisture over time after hardening, leading to tensile stress and surface cracking.

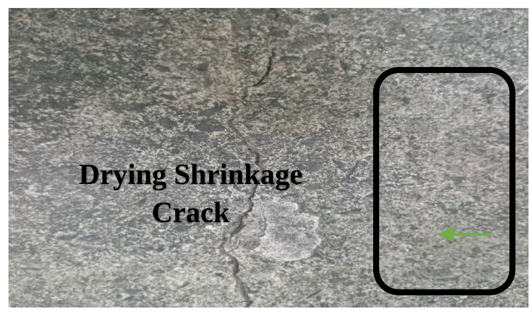

Fig. 5- Drying shrinkage crack

Remedial Measures of Drying Shrinkage Cracking

- Use strong formwork that doesn't bend easily.
- Fill cracks and tile joints with a mixture of acrylic polymer and white cement.
- Ensure formwork is completely waterproof to prevent leaks.
- Use a screed vibrator and float for smooth surface finishes.

3.8 Thermal Movement

Cracking in buildings often stems from thermal movement, which is influenced by temperature changes, the material's dimensions, its coefficient of thermal expansion, and other physical properties. When heated, most building materials expand, and when cooled, they contract. Regardless of where the structure's cross-section is located, this thermal expansion and contraction occurs [14]. Internal walls and floors experience minimal thermal variation, so they generally don't crack much. In contrast, external walls and roofs face significant temperature fluctuations and other physical factors, making them more prone to cracking, which requires careful consideration.

Remedial Measures of Thermal Movement

- It is best to design and build joints as slip joints, control joints, expansion joints, and construction joints.
- Use flexible materials in joints and connections to absorb movement.
- Design structural elements to manage thermal expansion and contraction effectively.

3.9 Chemical Reaction

Chemical reactions may arise from chemicals that come into contact with concrete after it has set, or from the components used to make the concrete itself. Expanding interactions between the silica-containing aggregate and the alkalis from cement hydration and admixtures can cause cracks in concrete over time. Concrete expands, cracks, and loses strength when external sulfates react with its constituent parts [15].

Remedial Measures of Chemical Reaction

- Choose safe aggregates: Use aggregates that don't react with alkalis.
- Use low-alkalinity cement: Prefer cement with alkalinity less than 0.5 (IS:456 limit is 0.6).
- Include pozzolanas: Add materials like fly ash and blast furnace slag, which have fine silicon and prevent reactions.
- Sulfate-Resistant Cement: For environments exposed to sulfates.
- Surface Treatments: Apply sealers or coatings to minimise chemical ingress.

3.10 Corrosion of Reinforcement

A well-designed and constructed concrete structure is initially water-tight, providing effective protection to the reinforcing steel inside it. This protection comes from a physical barrier created by a layer of concrete with low permeability and high density [5]. The concrete also offers chemical protection, preventing steel corrosion as long as the concrete remains impervious and alkaline with a high pH. Chemical reactions in building materials can lead to a considerable expansion in their volume. This expansion generates internal stresses within the materials, which can cause outward pressure and lead to the formation of cracks. Additionally, the materials that undergo these reactions tend to lose strength. Figure 6 demonstrates cracking due to corrosion of reinforcement, where rust formation leads to internal expansion and cracking of the surrounding concrete.

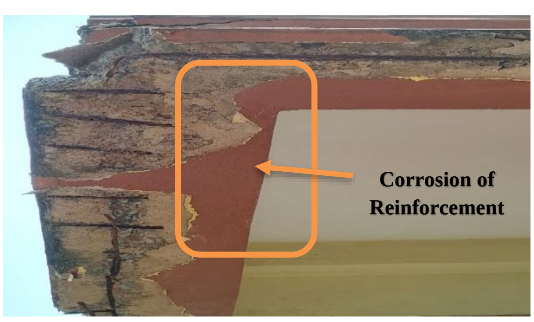

Fig. 6- Corrosion of reinforcement

Remedial Measures of Corrosion of Reinforcement

- Apply epoxy coatings to the reinforcement bars to protect them from moisture and corrosive elements.
- Use a higher-grade concrete mix for improved durability and strength.
- Put enough thickness on the cover.
- Incorporate corrosion inhibitors to reduce the likelihood of steel reinforcement corrosion.

3.11 Crazing

On the surface of the concrete, crazing appears as a network of tiny cracks. Less than three millimetres is the typical depth for these cracks [16]. These cracks generally appear as a delicate, complicated design and are only visible when the surface is wet or dusty. They can be visually unpleasant and could suggest imperfections in the surface, even though they do not affect the concrete's structural integrity. The majority of the time, crazing cracks only affect the surface of the concrete and don't go much deeper. When surfaces have been troweled smooth, they are more visible. Figure 7 illustrates crazing cracks—fine surface cracks forming a network, which are shallow and usually result from poor finishing or improper curing.

- Insufficient, poor, or curing.
- Wet curing and drying intermittently.
- Over-floating while completing
- Insufficiently fine particles on the surface.
- Sprinkling cement to dry up the bleed water.

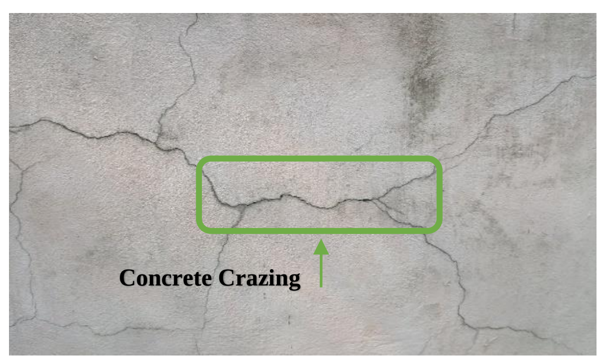

Fig 7- Concrete crazing

Remedial Measures of Crazing

- Start curing properly and promptly.
- Apply curing compound on the surface.
- Lightly grind the surface to remove crazing and refinish the material.
- Reduce exposure to moisture or use moisture barriers to prevent further crazing.
- Don't sprinkle dry cement or a cement-and-sand mixture on wet concrete.

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3.12 Poor Construction Practices

Negligence, greed, carelessness, or ignorance are frequently the causes of poor construction techniques. Both the owner and the construction company must place considerable emphasis on using high-quality materials and following the right construction methods in order to guarantee a structure that is structurally sound [7]. Any compromise in these areas can result in serious problems later on. Good practices are crucial for the building's long-term health and durability.

- Using unsuitable materials.
- Adding too much water to concrete and mortar mixtures.
- Control issues throughout concrete production, including batching, mixing, transport, placement, finishing, and curing.
- Construction-related overloads often exceed service-related loads.
- Not compacting the concrete enough.
- Placing construction joints in areas of high stress.
- Substandard plumbing and sanitary practices and materials.

Remedial Measures of Poor Construction Practices

- Monitor construction closely.
- Use high-quality materials.
- Ensure concrete is cured adequately to achieve optimal strength and durability.
- Place construction joints in low-stress areas to minimize potential damage and maintain structural integrity.

3.13 Structural Overloads

Concrete can become damaged when subjected to excessive weight, a problem that is often noticeable, especially on precast beams and columns, which frequently bear such loads [4]. Cracks that result from structural overload are typically one of the early signs of damage and tend to be visible without much difficulty. This early detection of cracks can help identify potential issues with the structure before they worsen. However, the downside is that once these cracks appear, they indicate that the concrete is already compromised and may require immediate attention to prevent further deterioration.

Remedial Measures of Structural Overloads

- Designers can prevent these cracks by limiting the weight on the structure.
- Replacing heavy materials with lighter alternatives to reduce the overall load on the structure.

3.14 Earthquake

Cracking occurs when there's a rapid shift in the Earth's deeper layers, often triggered by geological forces. These movements cause voids or empty spaces within the ground to collapse suddenly, leading to the soil above filling in the gaps. This process can happen due to various geological reasons, such as changes in pressure, shifts in tectonic plates, or natural subsidence. The result is a redistribution of earth materials, which may lead to surface cracks or ground deformation. These movements can be gradual or sudden, but they always involve some form of instability in the Earth's lower layers [17].

Remedial Measures of Earthquake

- Build structures on solid ground and use seismic-resistant designs.
- Secure heavy furniture and objects to the walls.
- The structure should be reinforced with connecting beams at various levels, such as the foundation, door, and roof levels.

3.15 Vegetation

The presence of vegetation, particularly fast-growing trees located near walls, sometimes leads to cracks as their roots exert pressure against the foundation. Tree roots typically spread horizontally in all directions, reaching as far as the tree's height above ground. Therefore, when trees are situated close to a wall, they should be carefully monitored for potential issues. This issue is more common in clay soil, where the roots retain moisture. Plants sometimes take root in wall cracks due to seeds from bird droppings [6, 18]. If not removed promptly, these plants can grow and eventually cause significant wall cracking. When the soil beneath a building's foundation is shrinkable clay, wall and floor cracks may develop either because growing roots dehydrate the soil, causing it to shrink and lead to foundation settlement, or because removing old trees causes the previously dehydrated soil to swell with moisture, such as rain, and exert upward pressure on the building. Figure 8 shows how vegetation, especially tree roots near a building, can lead to cracks in walls or foundations due to physical root pressure or soil moisture variation.

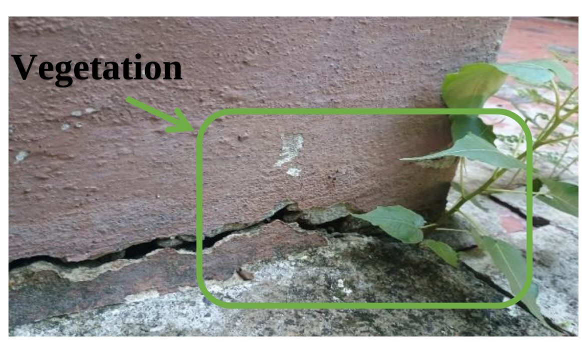

Fig. 8- Vegetation

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Remedial Measures of Vegetation

- To stop this, don't plant trees too close to buildings.
- Remove any small trees near walls quickly.
- Regularly monitor root growth to prevent foundation damage.
- If large trees are situated near a building and are not causing any issues, it is advisable not to disturb them, especially if the soil beneath the foundation is shrinkable clay.

3.16 Due to Creep

When exposed to continuous loads, some construction materials like concrete, brickwork, and timber- not only experience instant elastic deformation but also a slow, time-dependent deformation known as creep or plastic strain [19]. This creep consists of two components: the first, which eventually recovers once the load is lifted, is called delayed elastic strain, and the second, which results in a permanent deformation that persists even after the load is lifted, is called viscous strain.

Remedial Measures of Creep

- Use low-shrinkage and low-slump concrete.
- Cure concrete properly.
- Avoid formwork removal at early ages.
- Reduce operating temperatures.
- Lower the applied loads or stresses.
- Use design strategies to minimise stress concentrations.

4. Crack prevention techniques

4.1 Epoxy Resin Grout

Gravity-fed crack repairs usually require a polymer with low viscosity and surface tension, which improves the polymer's easy penetration of cracks [18]. The resin's viscosity is desired to be below 200 centipoise. Cracks must be thoroughly cleaned and dust-free before application. Routing techniques should be utilised if needed to facilitate the pouring of resin. The surface needs to be dried for 24 hours after using water to clean it, as any remaining moisture may block the flow of resin. With a flat rubber squeegee, remove any extra resin after continuously pouring the resin into the cracks until they are completely saturated.

4.2 Crack Stitching

This technique offers a long-term solution for fractured walls and masonry structural repairs. It includes drilling holes on both sides of the crack and then thoroughly cleaning them. After being cleaned, non-shrink grout is used to firmly place the legs of particular staples into the holes [9]. By putting the staples firmly in place, the grout reinforces the damaged area and gives long-term stability. This method is frequently utilised to strengthen walls and cure masonry cracks, maintaining the structure's integrity and minimising future damage over time. Figure 9 explains the crack stitching technique, which involves embedding metal staples into cracks to restore structural integrity.

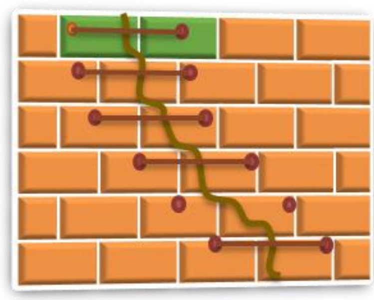

Fig. 9- Crack stitching

4.3 Drilling and Plugging

This method works best when the cracks are accessible from at least one end and have relatively straight paths. It is frequently used to repair vertical cracks, especially in retaining walls. When the cracks are linear and easily accessible, the process works well and allows for the right application of repair materials or methods [20]. Because these elements can hinder the procedure, it is not as useful for irregular or unreachable cracks. This method is frequently used when vertical cracks in retaining structures need to be effectively and efficiently managed because of its particular application.

4.4 Dry Packing

The process involves placing a mortar with low water content by hand, followed by compacting or tamping it into position. This method ensures the mortar is tightly packed and fills any gaps [21]. The compacting action, such as ramming, helps create a strong bond between the newly applied mortar and the existing concrete surface. By doing so, it enhances the adhesion and ensures proper integration of the materials, which is essential for repairs or applications where a solid connection between the new mortar and old concrete is needed for durability and performance. Figure 10 visualizes the dry packing method used for filling cracks or voids with low water content mortar, tamped into place for strong bonding.

Fig. 10- Dry packing

5. Conclusion

This comprehensive article sheds light on the widespread and unpredictable phenomenon of concrete cracking that has been bugging engineers, contractors, and maintenance personnel everywhere until today. Writing in a methodical approach, the article first describes the phenomenon of concrete cracking, a reminder that with improved building methods and materials or not, cracking is unavoidable. This is largely due to the intrinsic weakness of concrete, i.e., low tensile strength, and numerous external and internal stresses developed in the process of a building's existence. The second half deals with the very complex causes of cracking in great detail, both structural and non-structural causes. They are the flexural and shear stress, elastic deformation, shrinkage and drying (plastic), and movements due to temperature on one side and chemical reactions, corrosion of reinforcement, defects due to workmanship, creep, earthquake, effect of vegetation, and structural overloads on the other. All of them help degrade the concrete individually and may be initiated either at the beginning of the construction work or from the beginning of structural ageing. The paper also categorises cracks based on width and severity, and provides a thought-provoking framework for evaluation. Lastly, the third part elucidates remedial and preventive measures in detail. Remediation in the mode of epoxy resin grouting, stitch cracking, drilling and plugging, and dry packing is suggested as effective measures in tight and controlled cracks as and when they arise. Besides that, extreme care in advance is also taken for things like making proper arrangements for good quality material, curing properly, structural load checks, allowing space for thermal expansion, and observing good construction practices--all for the prevention of crack generation in the first stage itself. The major finding of this study is that although cracks in concrete structures cannot be avoided, their detrimental effects can be significantly alleviated to a large extent by early detection, proper diagnosis, and application of appropriate repair techniques and countermeasures. The right interpretation of crack behaviour, cause, and type not only allows engineers to select the correct remedial treatment but also guarantees the long-term durability, safety, and aesthetics of structures. In the future, better diagnostic tools, novel material science, and intelligent design methods will be able to conquer this old enigma. Through applied technology and scientific expertise combined, concrete construction experts can make concrete systems more robust and minimise the risk and cost of uncontrolled cracking.

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