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Design Parameters of Material Composites in Functionally Graded Concrete Layers

[1] Aditya B Shekhar, [2] Dr. Vidya Nitin Patil

[1] PhD Scholar, Civil Engineering Department, AISSMS College of Engineering, Pune, Maharashtra, India
[2] Professor, Civil Engineering Department, AISSMS College of Engineering, Pune, Maharashtra, India
Corresponding Author Email: [1] aditya8379@gmail.com, [2] vnpatil@aissmscoe.com

Abstract— ***Functionally graded materials (FGMs) have gained attention in the construction industry due to their ability to exhibit varying properties over their volume, tailored for specific performance requirements. This review focuses on the application of the FGM to cement-based materials, particularly concrete. Researchers have utilized a range of cementitious materials, including various cement types, fly ash, and fine and coarse aggregates from natural and crushed sources, to develop functionally graded concrete. Standardized testing techniques, like split tensile strength, bending/flexural strength tests, and compressive strength tests, have been used in experimental research to evaluate how these materials perform. The review provides a comprehensive overview of the materials employed and the testing methodologies adopted across multiple studies, highlighting the potential benefits of functionally graded cement-based materials in enhancing the functionality of construction elements.***

Index Terms— ***Tailored Materials, Functionally Graded Concrete, testing methodologies, Performance.***

I. INTRODUCTION

Cement-based materials are the most commonly used building materials [1]. The necessity to use resources efficiently led to the development of Functionally Graded Materials (FGMs). FGM is a material whose properties change gradually over its volume along multiple dimensions to effectively meet specific performance requirements [2]. The theory of FGMs has been applied to concrete elements such as beams, slabs, and pavements [3]-[7].

In 2006, during the Multi-scale and Functionally Graded Materials Conference, the theory of Functionally Graded Materials was first applied to cement-based materials [8]-[13]. Dias, C.M.R., Savastano Jr, H. and John, V.M. explored functionally graded fiber cement [14]. X. Wen et al. proposed a gradient structure concrete built on the principle of functionally graded materials [15]. Q. Li, S. Xu adopted the theory of functionally graded concrete [16]. S.T. Quek prepared functionally graded cement-based materials to improve impact resistance [17]. Wen, X. D., Tu, J. L., & Gan, W. Z. proposed a functionally graded structure concrete (FGC) built on the principle of functionally graded materials in splash zone [18].

II. MATERIALS

A. Cementitious Materials:

Cement:

Cement is commonly used in different grades and types for making concrete materials with the required strengths and properties. Sometimes, it was combined with other cement-like materials. Many researchers utilized ordinary Portland cement to cast reinforced cement concrete structural elements (RCC), Fiber-reinforced concrete (FRC), high-strength concrete (HSC), etc. [19]-[24]. Various types of cement including Portland-limestone cement, Portland Composite Cement, and Pozzolana Portland cement were utilized as binding agents for concrete casting [1], [25], [26].

Fly Ash:

Fly ash, a byproduct of coal burning, was utilized as a binding ingredient in concrete, replacing cement in large proportions to make the concrete more sustainable and perform better. Fly ash was utilized for producing a fine-grained cementitious mortar matrix, geopolymer concrete for marine artificial reefs, concrete mixes for increased sustainability and performance, high-volume fly ash concrete, and in combination with fine sand [27]-[31].

B. Aggregates:

Fine Aggregate:

Fine aggregates for concrete and grout mixes can be natural materials like river sand, siliceous sand, or diorite sand, or they can be crushed materials that pass through specific sieve sizes. The distribution of particle sizes, gradation, and fineness of these aggregates are important factors that affect the concrete's performance. Researchers have used diorite sand, river sand, aeolian sand, and crushed siliceous sand as fine aggregates to make concrete and grout mixes [18]-[21], [24]-[26], [28], [33].

Coarse Aggregate:

Coarse aggregates in concrete are natural materials like gravel, limestone, dolomite, and crushed stone. The size of these coarse aggregates can vary, typically ranging from 5 mm to 12.5 mm. They are mixed with fine aggregates to achieve the desired design and qualities of concrete mix.

Studies have used coarse aggregates from crushed natural stone, natural gravel, siliceous crushed aggregates, limestone gravel, and natural dolomite to produce concrete [19], [20], [24]-[26], [33], [34].

III. TESTS

A. Compressive Strength Test

This test determines the concrete's ability to withstand compressive loads.

Several investigations were carried out to test the compressive strength of various concrete mixtures and samples. The researchers commonly followed standards such as EN 12390-3, BS EN 12390-3, ASTM C39, BIS 516, and IS: 516-1959 to perform the compressive strength tests. The sample sizes ranged from 100x100x100 mm cubic specimens to 150x150x150 mm cubic specimens and cylindrical samples. The loading was typically applied at a constant rate, ranging from 0.3 MPa/s to 5 kN/s, until the samples failed. The compressive strength was measured by dividing the highest compressive load by the cross-sectional area of the test samples. Some studies also converted the cylinder strengths to equivalent cube strengths using correlation equations. The compressive strength tests were performed after 28 days of curing and, in some instances, also after 90 days [20]-[22], [24], [26], [34], [35].

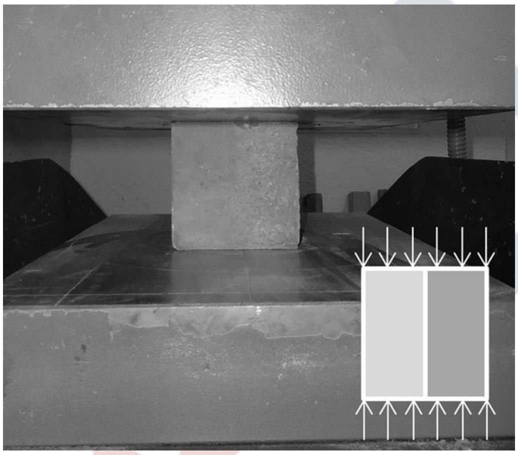

Fig. 1. Compressive Strength Test on a sample [24].

B. Split Tensile Strength Test.

This test measures the concrete's resistance to tensile forces.

The researchers have conducted split tensile strength tests on various concrete samples, following established standards such as ASTM C496/C496M-17, ASTM C496, and BIS 5816 (2004). The sample sizes generally varied from cylindrical specimens measuring 150 mm in diameter and 300 mm in height to cubic specimens measuring 100 x 100 x 100 mm. The loading was applied at a controlled rate, often between 0.016 N/mm^2 per second to 0.05 MPa/s, until the samples failed. The split tensile strength was subsequently calculated using formulas that considered the maximum load, specimen length, and diameter. Some studies also observed the crack development during the tensile strength tests. The split tensile strength evaluations were commonly conducted alongside the compressive strength tests, with the tests performed at 28 days and, in some cases, also at 90 days of curing [21], [22], [35], [36].

Fig. 2. Splitting Tensile Strength Test [35].

C. Bending Test / Flexural Strength Test

This test determines the flexural strength, load-carrying capacity, and deflection capacity of the concrete specimens.

Researchers have employed four-point bending tests to evaluate the flexural behavior and performance of various concrete specimens. The test setups typically followed standards such as ASTM C78/C78M-18, BS EN 12390-5/2009, ASTM C1609/C1609M-06, and ISO 21914, where the concrete beams or prisms were subjected to a four-point loading configuration. The researchers measured parameters like the applied load, mid-span deflection, and crack mouth opening displacement to evaluate the flexural strength or modulus of rupture, flexural strength at first crack, and residual flexural strengths. The specimen dimensions ranged from 100x100x500 mm beams to 180 x 30 x 8 mm prisms, with the loading applied at a controlled rate until failure [20], [22], [31]-[33], [37].

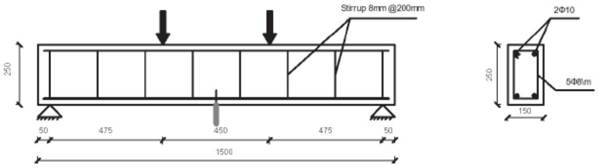

Fig. 3. Beam Details and Loading [33].

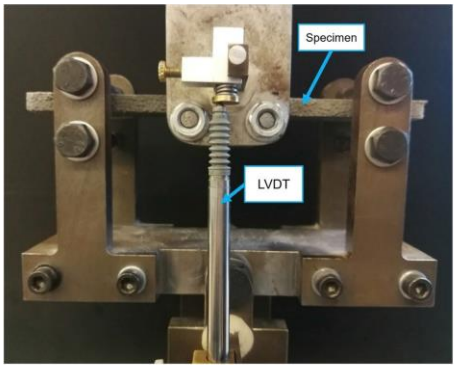

Fig. 4. Specimen loaded in four-point bending in the INSTRON 8872 [32].

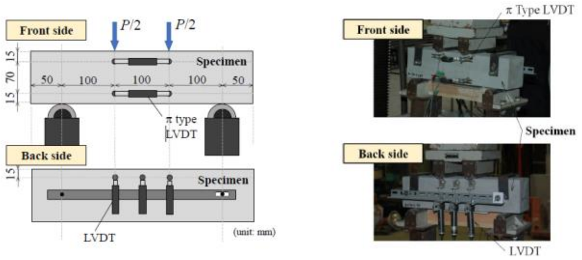

Fig. 5. Four-point bending test setup and positions of linear variable displacement transducers (LVDTs) [31].

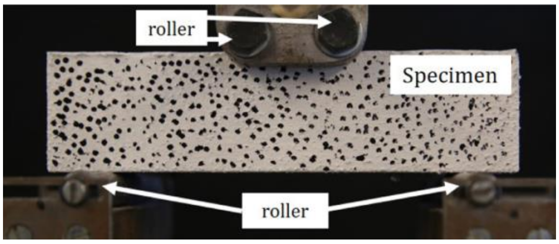

Fig. 6. Four-point bending experimental setup [27].

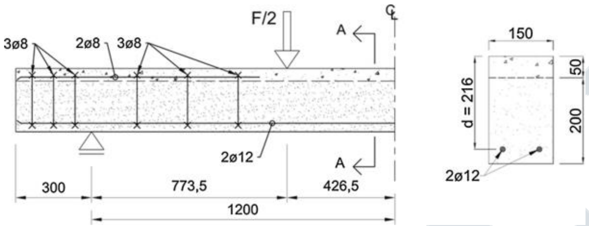

Fig. 7. Hybrid beams [37].

Some studies used three-point bending experiments to study the flexural performance of concrete. These tests were carried out under standards such as EN 14651/2010+A1 and ASTM C1609, where a concentrated load was applied at the mid-span of the beam specimens. The researchers measured the crack mouth opening displacement (CMOD) or vertical displacement to determine the post-cracking behavior and residual flexural tensile strengths of the fiber-reinforced concrete. The beam dimensions and loading rates varied across the different studies. [21], [34], [36].

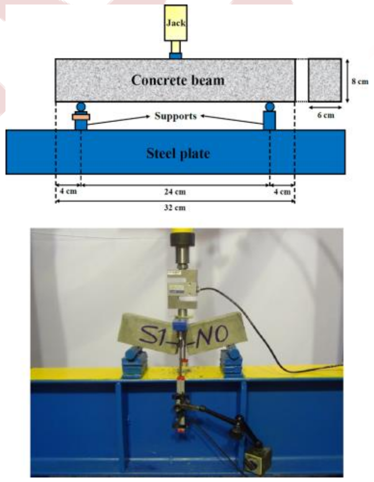

Fig. 8. Three-point bending tests on reinforced concrete beams [21].

In addition to the four-point and three-point bending tests, researchers have also conducted flexural strength tests following other standards. The tests were carried out on beam or prism specimens, which ranged in size from 100 × 100 × 500 mm to 150 × 150 × 500 mm, to evaluate the influence of factors like fiber concentration and water-to-cement ratio on the flexural behavior of concrete. The flexural strength tests were conducted as per BIS 516 (1959) and ASTM C293/C293M, measuring the applied load and mid-span deflection to determine the overall flexural performance. [26], [35].

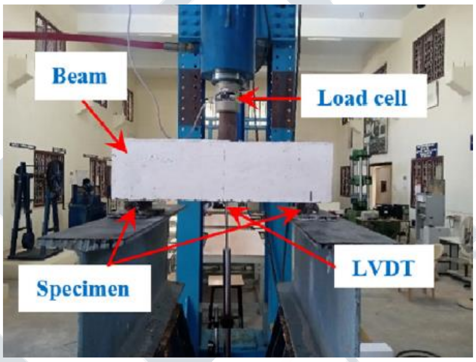

Fig. 9. Flexural strength test setup [26].

Fig. 10. Flexural Strength Test [35].

IV. CONCLUSION

There are numerous applications of functionally graded materials (FGM) to cement-based materials, particularly concrete. This approach holds significant potential for enhancing construction practices. The research findings indicated a wide variety of materials and methodologies being employed in the development and testing of functionally graded concrete (FGC).

In the production of FGC, various types of cement have been used, including Ordinary Portland Cement, Portland-limestone cement, and Pozzolana Portland Cement. Supplementary cementitious materials, notably fly ash, have also been utilized. Fly ash has shown promise in improving sustainability and performance when used as a partial cement replacement. Both natural aggregates (river sand, gravel) and crushed alternatives (siliceous sand, limestone) have been employed, each contributing distinctively to the property gradation within FGC structures.

Most of the investigators focused on FGC with 2-3 layers, though some investigations extended to 5 layers. The prevalence of 2-3 layered structures suggests a balance between the enhanced performance and practical manufacturability. However, the optimal number of layers likely depends on specific application requirements.

Functionally graded cement-based materials represent a promising frontier in construction technology. By enabling the tailoring of material properties to meet specific performance requirements of various construction elements (such as beams, slabs, columns), and applications (such as thermal insulation, impact resistance, acoustic performance, fire resistance, and durability in aggressive environments), FGC has the potential to significantly enhance the efficiency through optimized material use, sustainability via reduced consumption and improved durability, and functionality by enabling multi-purpose elements with tailored properties throughout construction projects. As research in this field progresses, it is anticipated that FGC will play an increasingly important role in addressing complex challenges faced by the modern construction industry, including structural optimization, resource efficiency, sustainability, durability, energy performance, and adaptability to diverse environmental conditions.

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