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Fracture Toughness of Hybrid Fiber-Reinforced Roller-Compacted Concrete Without Regard to Size

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Abstract

The purpose of the current study is to demonstrate that the fracture toughness of hybrid fiber-reinforced concrete (HyFR-RCC), which is calculated using a modified two-parameter model, is size-effect independent (MTPM). The fracture behaviour of seven series of single edge-notched specimens made of both plain-RCCs and FR-RCCs (single and hybrid reinforcements), subjected to three-point bending, is simulated using a micromechanical numerical model [1]. To determine fracture toughness, the MTPM is applied to the numerical load vs CMOD curves. A comparison is made with experimental values that are listed in the literature. In order to demonstrate the size-effect independence, RCC specimens of various sizes are computationally simulated, and the fracture toughness is then evaluated analytically using the MTPM.

Before being compacted, layers of dense-graded aggregates, sand, Portland cement, and water are often distributed with one or more bulldozers in a type of stiff-dry, zero-slump concrete called roller-compacted concrete (RCC). In the 1960s, RCC was originally used in the construction of dams before becoming well-liked in the years that followed for the paving of storage areas, municipal and industrial roadways, and dam repair [2-7].The enhanced placement speed and significant cost savings compared to traditional Portland Cement Concrete (PCC) were the main drivers of the growing interest in RCC engineering applications. This is mostly attributable to the RCC mixture's differing constituent proportions compared to the PCC mixture, with a higher ratio of fine aggregates allowing for tight packing and consolidation. As a result, it is possible to obtain a fresh RCC that is stiffer than normal zero-slump concrete. In actuality, the combination is wet enough to allow for appropriate mixing and distribution of the paste without segregation while at the same time remaining stiff enough to maintain stability under vibratory rollers.

Introduction

RCCs frequently experience complicated loading conditions as a result of their widespread applications, which can result in material fatigue cracking, fracture propagation, and a loss in mechanical performance. By optimising the water-to-cement ratio or by using various aggregates and additives, such as reclaimed asphalt pavement (RAP) ceramic waste aggregates ground calcium carbonate recycled concrete aggregates and industrial waste a number of studies have been carried out with the goal of properly designing the RCC mixture proportion.

Several types of reinforcement, including polymeric and natural fibres can be employed to enhance the mechanical and fracture behaviour of conventional concrete. Similar to this, a variety of reinforcing fibre types, including steel and polymeric fibres have been added to the RCC mixture to achieve the similar advantages seen with fiber-reinforced concrete (FRC) [8]. For example found that the addition of steel fibres increased the compressive strength and fracture energy of Fiber-Reinforced Roller-Compacted Concrete (FR-RCC) compared to a conventional concrete mix. Fracture toughness was often lower for FRC. The fracture performance of RCC with steel or polypropylene fibres was examined by other authors who noted that while the inclusion of fibres did not increase the RCC's flexural strength, it greatly increased the post-peak and residual strength capacity. The fracture characteristics, however, were comparable to or somewhat better than those of a regular FRC. Furthermore, recent research has shown that, in terms of fibre bridging ability during fracture propagation, FR-RCC has higher "fibre efficiency" than FRC A decreased water-to-cement ratio has been blamed for this behaviour because it increased friction between mortar and fibres.

Utilizing the advantageous interaction of the reinforcing phases, it is becoming more standard practise among well-known FRCs to use more than one type of reinforcement to enhance the performance of the composite materials Due to the synergistic effects of diverse fibre combinations, the so-called hybrid fiber-reinforced concretes (HyFRCs) are becoming more and more popular in multiple real-world engineering applications, including pavements, structural repairs, and offshore constructions.HyFRCs exhibit more effective fracture behaviour as a result of the fibres' positive contact, which is caused by the varied geometry and mechanical properties of the fibres.

A thorough analysis of the state of the art reveals that there aren't many published works on hybrid fiber-reinforced roller-compacted concretes (HyFR-RCCs), which calls for additional research Recent experimental research by has examined the fracture characteristics of HyFR-RCC notched specimens reinforced with a variety of steel and polymeric fibre combinations and put through three-point bending tests [9]. Through the use of the Modified Two-Parameter Model (MTPM), the fracture toughness in this work has been analytically estimated, and the impact of the reinforcing fibre combinations on such a parameter has been assessed.

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Subjective Heading

Some of the current Authors first proposed the MTPM, which is based on the well-known Two-Parameter Model in order to accurately predict the material's fracture toughness when crack deflection (kinked crack) manifests during the stable crack propagation, even in the case of far-field Mode I loading.The aforementioned MTPM has recently been applied to a variety of materials, including bone fiber-reinforced concrete and mortar and particleboard (PB), which exhibit internal heterogeneity and for which crack deflection has been experimentally demonstrated. Keep in mind that using the MTPM has shown to produce size-independent fracture toughness.

The purpose of this research is to demonstrate the size independence of the MTPM fracture toughness of HyFR-RCC. Here, the fracture toughness is calculated using a micromechanical finite element model in conjunction with the Modified Two-Parameter Model for specimens distinguished by the seven different HyFR-RCC mixtures examined in Ref [10-15].To be more specific, for each of the aforementioned seven HyFR-RCC specimen series: I the numerical model is calibrated by utilising the experimental data reported in Ref the load vs. Crack Mouth Opening Displacement (CMOD) curves numerically obtained are used, in conjunction with the MTPM, to compute the fracture toughness; and the specimen geometrical properties are taken into consideration when calculating the fracture toughness. sizes are made to vary in the numerical model and the corresponding fracture toughness values are computed.

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An Instron 8862 servo-hydraulic universal testing equipment was used to conduct the experimental campaign at the University of Parma's "Testing Laboratory of Materials and Structures".Three-point bending tests were performed on the specimens to assess the behaviour of the material during fracture. The TPM and the RILEM Recommendations were followed in the testing process, which was as follows: Each specimen was I monotonically loaded up to the peak load, Pmax, under Crack Mouth Opening Displacement (CMOD) control at an average rate equal to 0.1mmh1totally discharged under load control at the 95% Pmax during the post-peak period; and reloaded up to failure under CMOD control.

Discussion

More specifically, a non-linear 2D Finite Element (FE) home-made code written in the common Fortran language has been used to build the aforementioned micromechanical model. The code structure can be outlined in the following steps starting with the input data describing the specimen geometry, the material parameters, and the boundary and loading conditions: After defining the nodal load increment vector, dF, and computing the current displacement increment vector, dD, the stiffness matrix, called Keff, is computed and built; the stress and strain fields are then established in accordance with the constitutive laws of the material Then, using the stresses and strains in each finite element, it is determined whether the fiber-matrix interface separation, fibre failure, and matrix cracking conditions have been met. If so, the stress and strain fields are updated as discussed in Sections 3.2 and 3.3, and the internal and unbalanced force vectors are written. The convergence at the current load step is then checked in terms of the incremental displacement norm and the internal and unbalanced force vectors; if the required convergence conditions are satisfied, the calculation moves on to the next load increment by updating the stiffness matrix; otherwise, a new iteration starts at step No. 1. Up until the last load increase, the previous processes are repeated. Reference contains additional information. By using a homogenization technique based on the energy formulation put forward by Kalamkarov and Liu the macroscopic mechanical behaviour of the composite material is obtained. One matrix phase, indicated by the subscript m, and n distinct fibre phases contained in the matrix are what make up the heterogeneous (composite) material. The key premise is that the matrix contains each fibre phase uniformly, indicating that the composite is regarded as macroscopically homogeneous.Each component's volume fractions can be defined as follows.

The efficacy of the fiber-matrix bond deteriorates in fiber-reinforced materials, which has a negative impact on the stress distribution among the constituents. One of the most frequent damage mechanisms in fiber-reinforced composites is a phenomena called debonding, which is characterised by a partial or total separation between the phases of the composite. Debonding is a result of localised stress concentration at the fiber-matrix interface, which is brought on by both the materials' differing elastic characteristics and the geometric discontinuities created by the matrix-incorporating fibres.

Assuming a perfect bond between the fibres and the matrix provided in Section is written such that the fibre strain, f, is equal to the matrix strain along the fibre direction, mf. However, a strain jump, known as mf(x), is expected at the fiber-matrix interface when there is an unsatisfactory link between the fibre and the matrix. Such a strain leap can be expressed as where mf(x) and f(x) are the matrix strain along the fibre direction and the fibre strain, respectively. The generic spatial point designated by the vector x corresponds to such a strain jump. The strain jump is recast as to use a sliding function, s(mf(x)), to express a relationship that depends solely on the matrix strain.According to the sliding function varies along the fiber length, being a function of the vector **x**. However, since the fibers are short, it is more convenient to introduce a scalar sliding function, that is, the mean value of the sliding function s(εmf(x)) along the fiber axis, s(εmf¯). Consequently

The matrix is assumed to have a brittle behaviour in the current micromechanical model, and the discontinuities caused by the fracture process are simulated through a suitable alteration of the material properties. Since the aforementioned model is represented in a finite element code, in particular, the initiation of one or more finite element cracks is connected to the lowering of the stiffness of the current matrix in correspondence with the integration points. A cohesive-friction law is used to model the fractured zone in order to describe the matrix fracture process, whereas an elastic law is used to describe the non-cracked (continuous) region. In particular, it is believed that the fracture faces transfer a stress that is non-zero and is dependent on a continuous exponential law of the relative crack opening.

In order to calibrate the model, the micromechanical model discussed in Section 3 is used in this section to recreate the experimental campaign described in be more precise, the numerical load versus CMOD curves are first derived for each specimen series of the experimental campaign, and then the MTPM is used to calculate the fracture toughness. Following model calibration, the numerical model's specimen geometrical sizes are made to fluctuate, and then the aforementioned process is used to calculate the fracture toughness. The nominal sizes stated in Section are used to represent the prismatic specimens subjected to three-point bending force using a mesh. discretization composed of 366 four-node plate elements and by assuming a plane stress condition.The presence of the notch, with a thickness equal to 3 mm is also modelled.

Experimental evidence suggests that the matrix material's mechanical characteristics are as follows: While the mechanical characteristics of the fibre phases are described in Ref the Young modulus Em is equal to 27.94GPa, the Poisson's ratio vm is equal to 0.2, the ultimate tensile strength ft is equal to 3.96MPa, and the energy release rate Gf is equal to 40N/m. The fibres should be dispersed evenly throughout the matrix with random orientation. By applying a progressive vertical displacement to the top central loaded point and measuring the associated reaction force, the analyses are carried out under displacement control. Comparing the evaluated seven specimen series' vertical loads versus the experimental CMOD curves

It can be seen that the numerical approach that is, the micromechanical numerical model in conjunction with the MTPM) accurately predicts all of the experimental results, with errors in all cases being less than 10%. For the HFRC4 mixture, the highest inaccuracy in relation to I the peak load estimation is equal to about 2.9%; (ii) the elastic modulus estimation is equal to about 2.6%; and the fracture toughness estimation is equivalent to about 6.9%.

The numerical findings, as was previously noted, are in good agreement with the experimental data, demonstrating that the micromechanical model is capable of accurately estimating the material fracture toughness. In order to demonstrate the size-effect independence of RCC fracture toughness calculated by using the model in conjunction with the MTPM, such a model is used in the following. Four distinct models with varying geometrical sizes are taken into consideration for this purpose. More specifically, four scale factors (SFs) are taken into consideration, which are multiplied by each size of the examined specimen. Keep in mind that the SF = 1.00 instance corresponds to the simulated specimen sizes that were tested.

The composite is considered to be macroscopically homogeneous since it is expected that the characteristic length D of the body is bigger than the characteristic length d of the R.E.V. A similar premise, which is frequently used in the modelling of the mechanical behaviour of finite random heterogeneous entities, can be used to find the average properties of the composite material. By comparing the virtual work rate assessed in the composite material with that associated with a homogenised comparable material, this objective can be achieved.

Conclusion

The fracture behaviour of single edge-notched specimens made of both plain RCCs (without fibres) and fiber-reinforced RCCs (single and hybrid reinforcements) has been simulated in the current work using a micromechanical numerical model. Seven specimen series with various fibre contents and materials were taken into consideration, and the generated numerical load versus CMOD curves were utilised to apply the Modified Two-Parameter Model to calculate the elastic modulus and fracture toughness of the material. The outcomes were contrasted with experimental data that was published in the literature. All experimental values have been found to be well predicted, with errors in all cases being less than 10%; more specifically, the maximum error is equal to approximately 2.9% (HFRC4 specimen series) for peak load, 2.6% (HFRC4 specimen series) for elastic modulus, and 6.9% (HFRC3 specimen series) for fracture toughness.

Finally, four distinct models in terms of geometric sizes have been taken into account for the seven specimen series, and the relevant values of elastic modulus and fracture toughness have been analytically computed using the MTPM based on the numerical load versus CMOD curves. For all specimen series, it has been found that the estimated values for elastic modulus and fracture toughness are almost identical to the corresponding averaged experimental values, regardless of the specimen sizes, and fall within the experimental standard deviation error limits.

The fracture toughness derived by using the micromechanical model in conjunction with the MTPM is a size-independent quantity, meaning that it solely depends on the material, according to the above satisfactory results. For estimating the fracture characteristics of fiber-reinforced cementitious-based composites, the micromechanical numerical model used in this study has proven to be an effective tool.

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Conflict of Interest

The authors declare that there are no conflicts of interest.

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