Sisal fibre pull-out behaviour as a guide to matrix selection for the production of sisal fibre reinforced cement matrix composites

Authors
Joe Mapiravana, PhD
Mandla Dlamini, B(Eng.)(Civil)

Affiliation
Construction Materials and Methods Research group, Building Science and Technology (BS&T), Built Environment Unit (BE), Council for Scientific and Industrial Research (CSIR).
Physical Address

Building 2, CSIR Meiring Naudé Road; Brummeria; Pretoria; South Africa.
Speaker email address: mdlamini@csir.co.za
email address: jmapiravana@csir.co.za

Natural fibre reinforced cement composites are promising potential materials for use in panelised construction. The structural properties of these composite materials are yet to be fully understood. As the role of the natural fibre is to reinforce the composite in tension and improve the toughness of the system, the mechanisms of failure and the effect of sisal reinforcement in potential matrices were investigated.

This study sought to understand fibre pullout as a failure mechanism in sisal fibre reinforced cement composites and to select optimum cement composite matrices from a range of potential cement blends. Single fibre pull-out tests were carried out to determine the optimum matrices for fibre/matrix bonding for three generic types of matrices of varying basicity ratio [(CaO+MgO)/ SiO_2] in the $Al2O_3$-SiO_2-CaO ternary composition system. The embedded length of the sisal fibres was varied to establish the critical lengths for a specific failure mechanism. Curing time was also taken into account to establish the optimum curing conditions for maximum energy absorption or release on fibre pullout.

5x10x20 mm cement composite beams were cast with a single sisal fibre strand per sample along the neutral axis of the beam length. The beams were subsequently cured in water and tested in a tensile machine, where the fibres were pulled out from the cement composites. The mechanism of failure was determined from; SEM images of the fibres pulled from the matrices, pullout shear stress-strain data, the measured stiffness (dynamic Young modulus) and the porosity of the cement composite matrix. From this data, the matrix with the highest pullout stresses and highest energy absorption was selected. The maximum fibre length to ensure fibre pull-out rather than fibre fracture (critical length) was also determined.

The strength of the sisal fibre/matrix bond and anchorage relative to the Young modulus (stiffness) influenced the fibre pullout mechanisms. Matrix shear was the dominant failure mechanism in low stiffness (high porosity) matrices whereas matrix/fibre de-bonding was predominant in high stiffness (low porosity) matrices.

1.Introduction

The use of fibre in cement composites as a crack mitigation and reinforcement technique is not new. A lot of work has been done on various fibre types including steel fibres, glass fibres, and propylene fibres. However, not much attention has been given to the incorporation of natural fibres in cementitious materials. This may be due to concern on the durability of natural fibres when used in cement/mortar matrices.

The challenge in using brittle fibres like sisal in structural cement composites is ensuring energy absorption on composite failure. It is proposed that fibre-matrix debonding and matrix shear are forms of natural fibre composite failure which increase the absorption of energy of composites under tensile strain. The compatibility of fibres with the surrounding matrix is extremely important if one aims to design for high energy absorption upon failure. It has been postulated that the fibre could rupture if the matrix is too stiff and cause an overall brittle system failure, or at the under end of the spectrum, if the matrix has insufficient stiffness, the fibres could pullout at very low forces and with minimal energy absorption upon failure. It is there fore imperative to ensure that an optimum matrix is selected for sisal fibre reinforcement.

In this study, sisal fibres were introduced into cement composite matrices to form fibre reinforced cement composites. The composites were then cured and tested in single fibre pullout tests.

2.Literature Review

Natural fibres in cementitious matrices have been used in the past for thin walled panels in Brazil) and in Tanzania as roof tiling [2].There is general consensus on natural fibres ability to toughen cementitious matrices. A major concern however has been long term durability of sisal fibre reinforced cement based matrices. Silva and Fihlo (1999) reported that the long term embitterment of fibre-cement based composites can completely be avoided through the use of a cement matrix free of calcium hydroxide (CH) [1]. The results showed that it was possible to dramatically reduce the CH content of the matrix, while maintaining or even improving its mechanical properties through the addition of an extender.

Persson and Skarendh (1980) studied sisal fibre-concrete for roofing sheets and other purposes. The influence of matrix strength, fibre content and fibre arrangement on the flexural strength of the composite was investigated. They concluded that an increase in matrix quality, keeping constant the volume fraction of fibres, increases the flexural strength of the composite. However keeping the quality of the matrix constant and increasing the volume fraction of the fibres increased the post cracking capacity of the composite[4].

Bessel and Mutuli (1982) did tensile tests on sisal fibre reinforced cement matrices. They attempted to quantify the interfacial bond by measuring the crack spacing resulting from the tensile load acting on the composite. They found the mean fibre/matix interfacial bond to be 0.6 Mpa with a standard deviation of 0.26 MPa[6].

Da silva et al (2008) investigated the monotonic tensile behaviour of high performance sisal fibers, they concluded that Mechanical testing of small diameter fibers was not trivial. The The Young's modulus of sisal fibers, corrected for machine compliance, was around 18 GPa. The modulus was not influenced by the gage length. The strain-to-failure decreased from approximately 5.2% to 2.6% when the gauge length was increased from 10 mm to 40 mm which could be explained by the varying cross sectional area of the fibre over its length. Tensile strength, on the other hand, was found to be independent of the gage length. The Weibull modulus decreased from 4.6 to 3.0 when the gage length was increased from 10 mm to 40 mm, respectively[7].This was due to the increased presence of flaws along the fibre length.

A critical fibre length value for sisal fibres gives a value for which the failure mode will change from fibre pullout to fibre rupture. In Portland cement matrices, the critical fibre length was determined by a study by Morrissey & Coutts (1985). Sisal fibres were embedded at lengths ranging from 10mm to 60mm. it was found that the critical length of embedment for sisal fibre was approximately 30 mm[5].

3.Experimental Work

3.1 Fibre Preparation and treatment

Individual fibres or bundles of fibres were isolated and manually stretched to breaking point to eliminate processing flaws in the fibres. This treatment was repeated to eliminate as many flaws as possible from fibre lengths that were inserted into matrices for pull-out tests. The remaining shorter and shorter fibre lengths became stronger and stronger as the weakest links (largest flaws) were progressively removed in this way. This limited the possibility of fibre breakage during pull-out tests and greatly enhanced pull-out as the designed failure mechanisms during the tests.

3.2 Matrices

The 6 composite matrices that were tested were of varying basicity ratio [(CaO+MgO)/ SiO2] in the Al2O3-SiO2-CaO ternary composition system, the seventh, a control composite matrix was ordinary Portland cement. Two groups of materials were used, 3 of the six specimens were designated as A1 A2 and A3, and the rest were designated B1, B2 and B3 as showing in figure 1. The Portland cement matrix was designated PC. The proportioning of the various materials in each group of specimens, A and B, produced varying properties such as, stiffness, porosity and strength. This variability in matrix properties was used to determine key matrix properties that influenced the energy absorbed during fibre pullout.

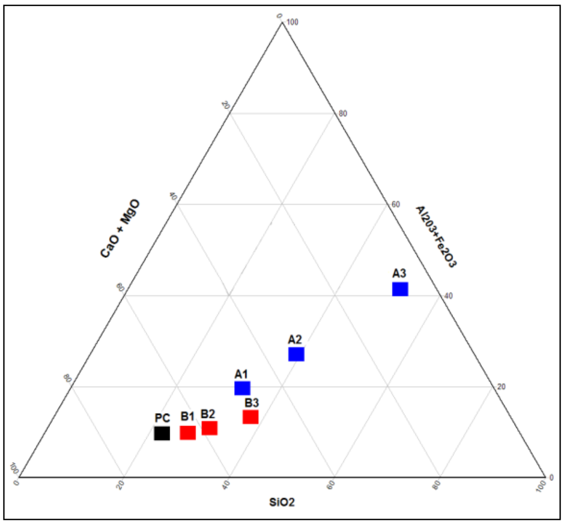

Figure 1: Compositions of the A+ B series

Test specimens were cast in Perspex moulds with the following dimensions 20mmX5mm X10 mm.

Figure 2: Test specimens being cast (half of mould length)

Figure 2 shows cast test specimens which consist of cement composite matrix with a single strand of sisal fibre running along the centre of the specimen. The notches along the Perspex mould ensured that the fibres were located in the middle of the specimens.

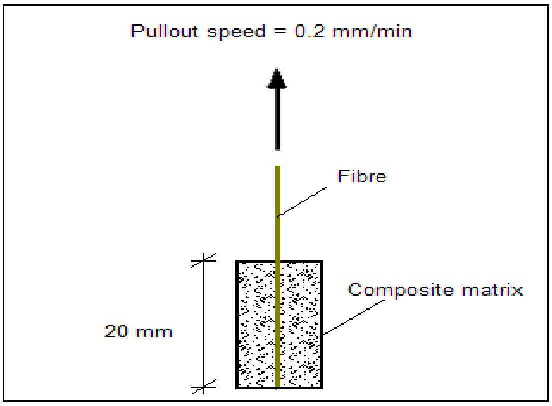

Figure 3: Diagram showing the fibre pullout test and materials

After 7, 14 and 28 days of curing, the pullout behaviour of the fibre reinforced specimens was tested under single fibre pullout conditions in a calibrated tensile tester.

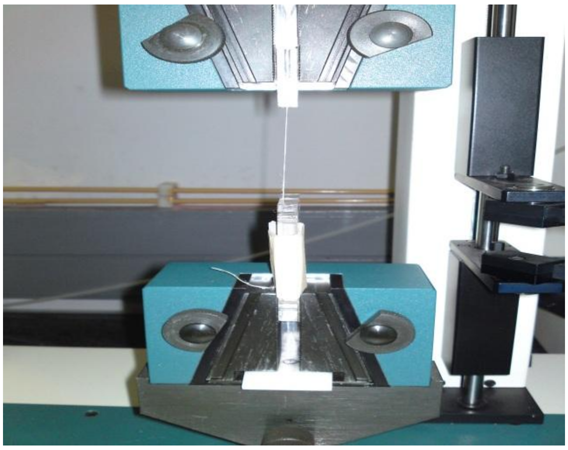

Figure 4: Single-fibre pull-out test assembly.

The free end of the fibre was super glued in a 0.2mm hole drilled in a Perspex slab held by the top claps that were attached to the load cell. The pullout speed was fixed at 0.2 mm/minute. The pullout resistance over time could then be plotted for each specimen.

3.3 Matrix properties

Mechanical properties of the matrices such as their stiffness were obtained through BET measurements. From these tests the BET dynamic stiffness and the porosity of the matrices were measured.

3.4 Data analysis

The stress shown in the graphs was calculated as the shear stress at the interface of the fibre and the matrix. The embedded length of the fibres and the SEM images were used to determine the dimensions of the fibres. To estimate the shear stress it was assumed that the fibres imbedded in the matrix had a circular cross section and the average of 3 diameter measurements was used to calculate the shear area.

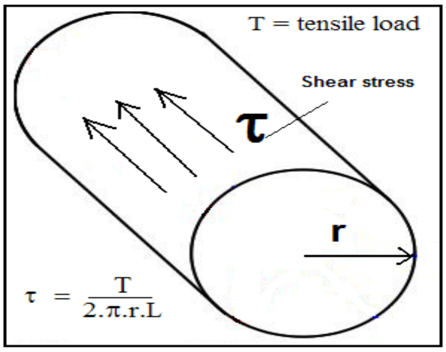

Figure 5: Shear stress on a circular prism fibre

Furthermore, the mode of failure was further characterised through SEM images of fibres pullout out from the various matrices.

The area under a typical stress strain diagram gives an indication of a materials toughness and capacity to absorb energy when loaded to failure. However strain would be difficult to measure in a pullout test and the interest of this study was to gauge the energy dissipation capacity of a matrix compared to other matrices. To this end stress time graphs such as the one show in figure 6 below were used.

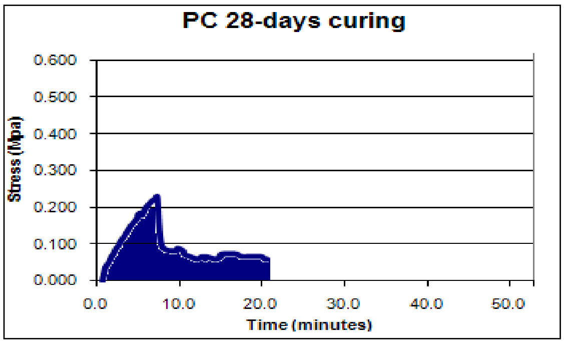

Figure 6: Shear stress time diagram

The area under the stress versus time curve was an indicator of the extent of the energy absorption during the fibre pullout test. The larger the area the higher the energy absorption due to all energy dissipation mechanisms that absorb the strain energy associated with the pull-out test. The corresponding units to this energy absorption measure for mathematical purposes be MPa*minutes. No strain was detected over time until the fibre pull-out or fracture. Fibre lengths that were pulled out were observed under SEM to determine the pull-out fracture mode(s).

4 .Results

4.1 Introduction

The fibre pullout tests on the various specimens revealed three distinct failure modes. Matrix shear, fibre matrix debonding and mixed failure mechanism(matrix shear and fibre/matrix debonding). Given below are the stress time relationships of specimens and SEM images of the corresponding fibres that were pulled out.

4.1 Matrix shear failure

Figure 7 shows the typical stress time failure curve for low stiffness matrices. The bond between the matrix and the fibre was higher than the shear resistance of the matrix. This resulted in matrix exhibiting a brittle failure mechanism.

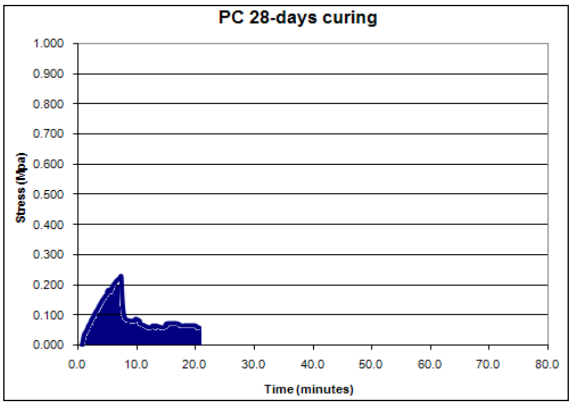

Figure 7: matrix shear failure

The SEM image (Figure 8) of the specimen confirms to us that the mode of failure was matrix shear because the fibre was completely covered in cementitious particles, with no evidence of matrix fibre de-bonding.

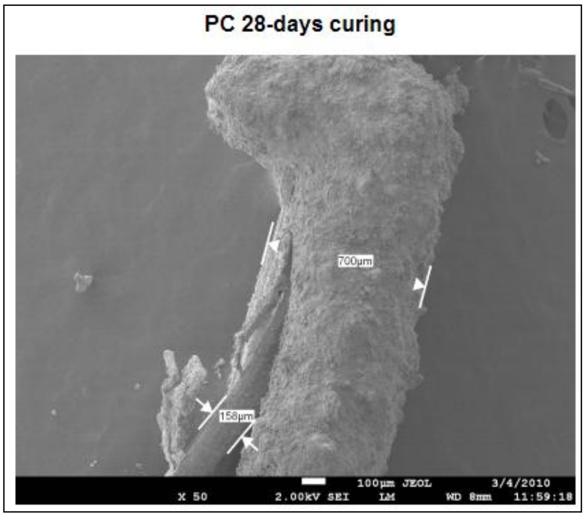

Figure 8: PC 28 days SEM image

4.2 Mixed failure mechanism

Specimen A2, after 14 days, showed high energy absorption. The stiffness of the matrix was 4.2 a value in the lower to mid range of stiffness's measured after 14 days curing. Figure 9 shows the stress time relationship of the specimen under fibre pullout conditions.

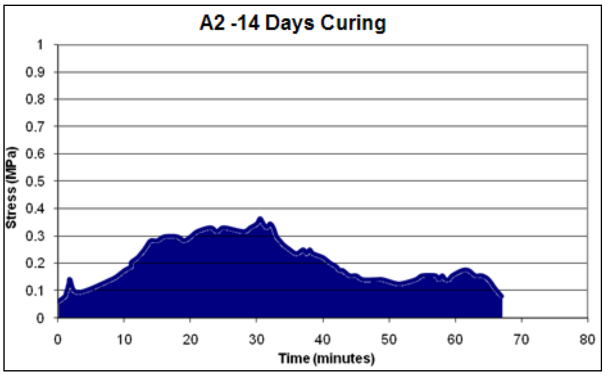

Figure 9: Stress –time pullout behaviour of Specimen A2 14 days curing.

Figure 10 shows the SEM image of the fibre pulled out of the A2-14 day cured matrix. There is evidence of fibre matrix de-bonding on some parts of the fibre and evidence of matrix shear on other parts of the fibre. This is observed by the mix of clean fibre surfaces and remaining cementitious material along the surface of the fibre.

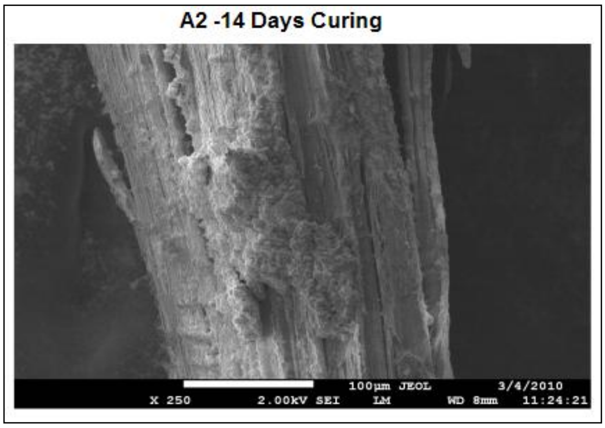

Figure 10: Specimen A-2 SEM image (fibre matrix debonding and matrix shear)

4.3 Fibre de-bonding mechanism

Sample B-2 14 days curing, had a stiffness of 7.8 GPa, which was high relative to the stiffness's of the other matrices. Figure 11 shows the behaviour of the shear stress –time behaviour under fibre pullout conditions. It is clear that this specimen did not absorb much energy, and from figure 13 it can be deduced that this was due to the high stiffness of the matrix.

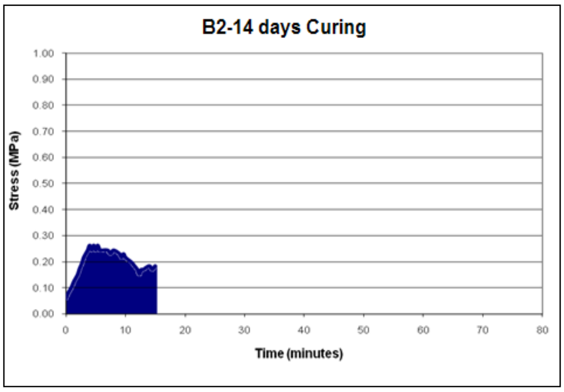

Figure 11: Stress –time pullout behaviour of Specimen B2 14 days curing

The SEM image of the fibre (Figure: 12) shows that the dominant mode of failure in this specimen was fibre matrix de-bonding. The upper portion of the fibre still has some cementious material attached to it, however it was minimal and the major portion of the fibre is clean of cementitious materials.

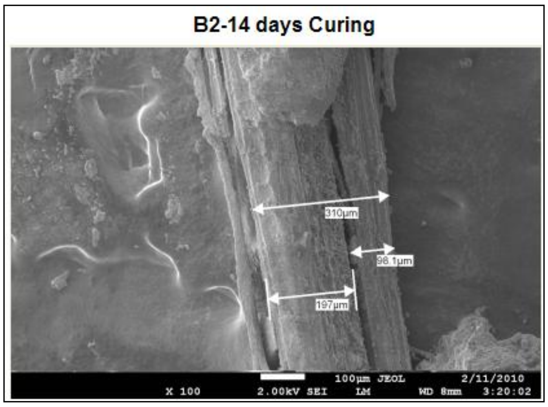

Figure 12: Sample B-2 14 days

As discussed earlier, the area under the graph was used as an indicator of the energy absorption of the system under fibre pullout stresses. The young modulus was plotted against the area under the graph (energy absorption indicator. Figure 7 below shows the results.

A polynomial best fit curve was applied to the data. It is thought that there could be an optimum matrix stiffness when maximizing pullout energy absorption.

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5. Discussion

High stiffness matrices largely failed via fibre/matrix de-bonding. From figure 13 it can be seen that high stiffness matrices did not absorb much energy during fibre pullout failure.

The balance between fibre/matrix de-bonding and matrix shear when mixed mode energy absorption mechanisms occurred depended on the relative strength of the fibre/matrix bond to the matrix strength that depended on stiffness (E) and, therefore, porosity and fracture energy of the matrix. Figure 13 showed that medium stiffness matrices (4-6 GPa) gave the highest energy absorption values. It is suspected that this matrix stiffness range allowed a mixed failure mode consisting of fibre de-bonding and matrix shear.

It appears that the amount of energy absorbed by the matrix was affected by its mechanical properties and, to a large extent the young modulus of the specimen (E-value). The bond strength of the matrix to the fibre was another key determinant of the mechanism of failure.

For a given system, where matrix shear was the sole or dominant energy absorption mechanism the matrix stiffness was relatively low. From figure 13 it can be seen that low stiffness matrices (after 14 days water curing) did not show very high energy absorption characteristics.

The table 1 shows the stiffness and a description of the observed failure of the specimens at after 14 days of water curing.

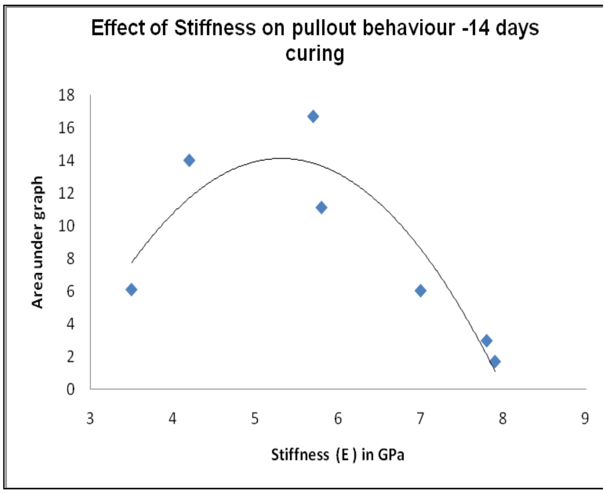

Figure 13: Stiffness (Young Modulus) vs Area under the stress-time graph (energy absorption)

Figure 13 is a plot of the dynamic stiffness of a matrix versus the area under the stress time graph of specimen under fibre pullout. To a large extent there is a reasonable amount of scatter in the data. A parabolic best fit curve was fitted to the data as a linear relationship was not logical. From this data it is postulated that the stiffness of a matrix does affect the pullout behaviour of fibres. The fibre matrix bond and surrounding matrix stiffness seem to be the two primary variables controlling the failure mode of a composite system. For low stiffness matrices it was observed that a low amount of energy was absorbed by the system, the predominant failure type was matrix shear which indicates (see figure 7 and 8) that the fibre matrix bond was stronger than the matrix strength. On the other extreme it can be seen from figure 13 that very stiff matrices (7-8 GPa) also failed to absorb energy, the predominant failure mode in these systems was fibre matrix de-bonding. This indicates that the fibre matrix bond for these systems was weaker than the matrix strength. The matrices with the highest energy absorption were in the intermediate stiffness range (4-6 MPa), where the predominant failure mode was a mixed mode (fibre de-bonding and matrix shear).

6. Conclusions and recommendations

From the results reported on in this study it is concluded that:

Table 1: Failure mode and matrix stiffness

Matrix	Pull-out Energy Absorption Mechanism(s)	E/GPa
A1	Largely fibre/matrix de-bonding	5.8
A2	Largely fibre/matrix de-bonding and minor matrix shear	4.2
A3	Matrix shear	3.5
B1	Matrix shear and fibre/matrix de-bonding	5.7
B2	Largely fibre/matrix de-bonding and minor matrix shear	7.8
B3	Fibre/matrix de-bonding and matrix shear	7
PC	Matrix shear and fibre/matrix de-bonding	7.9

- The matrices with the highest energy absorption showed a mixed failure mode of matrix shear and fibre matrix de-bonding.
- There was an optimum range of stiffness values for high energy absorption upon fibre pullout.
- Low stiffness matrices exhibited low energy absorption due to matrix shear
- High stiffness matrices exhibited low energy absorption due to fibre matrix de-bonding.

It would be very difficult to establish the fibre matrix bond strength, however from this work it may be inferred that the fibre matrix bond strength development is independent of the matrix shear strength development over time.

From the work it may also be concluded that a minimum or critical length of fibre embedding can only be determined for a matrix of known stiffness and that this value will change with varying matrix stiffness.

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6. References

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