

THE EFFECT OF SECONDARY FIBRE REINFORCEMENT ON DYNAMIC RESISTANCE OF ULTRA-HIGH-PERFORMANCE CONCRETE

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ABSTRACT. This study compares the dynamic initiation fracture toughness of five fibre-reinforced concrete materials with different types of fibre reinforcement. The base material was steel fibre-reinforced ultra-high-performance concrete (S). Four additional materials were created by incorporating various secondary fibre reinforcements into the base mix: aramid (SA), polyvinyl alcohol (SPVA), carbon (SG), and polypropylene (SP). Dynamic fracture initiation toughness was determined by conducting medium-speed tensile tests on double-edge notched specimens. These tests were performed with a modified Instron Ceast 50 J instrumented Charpy tester, using a striking velocity of 3.8 ms^{-1} and a total impact energy capacity of 7.5 J. The polypropylene fibre-reinforced concrete (SP) exhibited the highest average dynamic initiation fracture toughness ($171.4 \text{ kPam}^{0.5}$) and also demonstrated the greatest impact toughness.

KEYWORDS: Fibre-reinforced concrete, dynamic fracture, Charpy test, fracture toughness.

1. INTRODUCTION

It is important to characterise the mechanical properties in order to select the most appropriate materials for specific structural components. For concrete and concrete composites, the primary properties of interest are generally compressive strength, elastic modulus in compression, and bending strength. However, certain applications necessitate determining the static and dynamic tensile strength, as well as dynamic fracture toughness [1, 2]. This is the case in situations involving earthquakes, explosions (e.g. terrorist attacks), car crash tests, and similar events. Further applications include the protection of infrastructure against blasts and ballistics. Reinforced concrete beams loaded in bending, commonly used in bridges [3], are another example. The reliable operation of reinforced concrete structures depends on their adequate dynamic fracture toughness. Generally, impact loading fracture toughness can be quantified as:

- (1.) dynamic fracture initiation toughness,
- (2.) propagation fracture toughness,
- (3.) arrest toughness.

Among these, the initiation fracture toughness is the most crucial fracture mechanics parameter.

It is important to distinguish these tests from those typically performed according to standards for metallic materials. The most commonly used ones include:

- ASTM E1820: This standard defines methods for determining fracture toughness, including dynamic

fracture toughness. It covers different types of tests, such as impact bending test and compact specimen test,

- ISO 22156: This standard specifies a test method for determining dynamic fracture toughness using a hammer impact test,
- EC 2291: This European Standard also specifies a test method for determining the dynamic fracture toughness of steel.

The cases mentioned above represent a very complex loading regime, often accompanied by elevated temperatures. The appropriate formulation of the material composition, especially in the area of fibre reinforcement, is crucial to achieve high resistance to this type of loading. To enhance the tensile strength and fracture toughness of concrete, steel fibre reinforcement is often used. Hybridising the fibre reinforcement can further improve the response of the concrete to impact loading. The combination of fibre reinforcement, when properly designed, also provides the additional benefit of increased resistance to heat, which is crucial in the case of blast loading associated with elevated temperatures.

The purpose of the presented research is to obtain data allowing a deeper insight into the fracture behaviour of high-performance concretes with hybrid fibre reinforcement to expand the knowledge needed for the advanced design of materials for applications under extreme conditions.

2. EXPERIMENTAL SETUP

2.1. PREPARATION OF MATERIALS

Concrete slabs were cast using ultra high-performance concrete with various compositions of fibre reinforcement. The base matrix was prepared from Portland cement CEM I 52.5 R (850 kg m^{-3}) produced by Aalborg, silica sand with a grain size of 0–0.5 mm from Strelec quarry (990 kg m^{-3}), Quartz powder with a mean grain size of $4 \mu\text{m}$ produced by Microdorsilit Chejn (200 kg m^{-3}) and Elkem 940 U microsilica fume (150 kg m^{-3}). Superplasticizer Glenium ACE 430 (Polycarboxylic) has been added to reduce the need for mixing water (25 kg m^{-3}). Steel fibres DM 6/0.17 produced by KrampeHarex (6 mm long and 0.17 mm in diameter) have been used as the main fibre reinforcement at 1.5% volume fraction. Four types of fibres were selected for the secondary reinforcement; polypropylene (PP), polyvinyl alcohol (PVA), carbon (G), and aramid (A) fibres. The Hobart N50 mixer was used for the homogenisation of individual components. Initially, the dry ingredients were blended for 2 minutes, followed by the addition of water and superplasticiser. Subsequently, steel fibres were incorporated, followed by the secondary fibres in the final stage of the mixing process. After curing in the water tank for 28 days, the slabs were cut into the shape illustrated in Figure 1 using a water jet to prepare the test specimens.

2.2. IMPACT TENSILE TESTS

For brittle solids like ceramics, rocks, and concretes, specialised specimen geometries, different from those used in standard metal fracture tests, have been developed for dynamic fracture initiation toughness measurements. In this study, specimens shown in Figure 1 were used.

It is well established that the dynamic fracture behaviour of materials is related to the loading rate. Numerous studies have shown that dynamic fracture toughness differs significantly from quasistatic fracture toughness because it is a loading rate-dependent material property [4, 5]. In dynamic tests, the peak load increases proportionally with the loading rate [6]. The measurement of the quasi-dynamic tensile strength of special concrete specimens is described in [7], while the dynamic properties of reinforced concrete, focused on both the tensile strength and fracture toughness, are investigated in [8]. The results of the tests performed in this study are given in Tables 1 and 2.

2.3. IMPACT FRACTURE TOUGHNESS

Peak impact force, while readily measurable, does not provide as complete a picture of a material's fracture behaviour as fracture toughness does. Furthermore, fracture toughness enables more meaningful comparisons between materials. For these reasons, we converted the peak impact force to the stress intensity factor, K_I . Since this conversion is based on

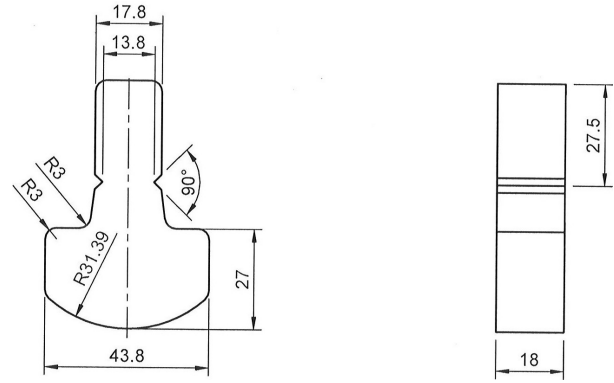


FIGURE 1. Special specimen for impact tension test.

Specimen	Material				
	S	SA	SPVA	SG	SP
1	208.4	345.9	259.4	376.0	649.7
2	401.7	258.5	407.8	314.3	593.7
3	284.2	201.0	313.3	557.2	758.7
4	548.8	468.1	413.4	431.0	461.9
Mean	360.8	318.4	348.5	420.0	616.0
St. deviation	128.6	100.7	65.0	90.0	107.0

TABLE 1. Peak forces F_{\max} [N] during the impact loading.

Specimen	Material				
	S	SA	SPVA	SG	SP
1	0.7	1.2	0.9	1.2	2.2
2	1.3	0.8	1.4	1.0	2.0
3	1.0	0.7	1.05	1.8	2.7
4	1.9	1.6	1.4	1.5	1.6
Mean	1.2	1.1	1.2	1.4	2.1
St. deviation	0.4	0.4	0.3	0.3	0.4

TABLE 2. Impact work of fracture W [J].

the maximum force under impact loading, the resulting K_I value represents the critical K_I , and thus the fracture toughness, which we designate as K_{Id} (dynamic fracture initiation toughness). Equation (1) from [9], with notches treated as cracks, was used for calculating K_{Id} :

$$K_I = \sigma \sqrt{\pi a R} \left(\frac{a}{b} \right), \quad (1)$$

where:

$$\sigma = \frac{F}{A_0},$$

F is the loading force,

$A_0 = 2B(a + b)$ is an un-notched cross section of a specimen,

a is the depth of the crack (notch),

b is the complement to the half of the width of the specimen,

B is the thickness of the specimen,

$$R\left(\frac{a}{b}\right) = \frac{1.122 - 0.561\left(\frac{a}{b}\right) - 0.205\left(\frac{a}{b}\right)^2 + 0.471\left(\frac{a}{b}\right)^3 - 0.190\left(\frac{a}{b}\right)^4}{\sqrt{1 - \frac{a}{b}}}$$

The geometry of the specimen is illustrated in Figure 2.

Table 3 shows the calculated stress intensity factor values, which are further illustrated in probability density distribution diagrams in Figures 3 through 7. A summary of these distributions for all five tested materials is shown in Figure 8. The means and standard deviations are also illustrated in Figures 3–7.

As can be seen from these figures, adding propylene fibre reinforcement to steel fibre reinforced concrete results in superior performance compared to other reinforcement materials.

Impact fracture work (W) is also an important quantity when considering the resistance of a material to fracture under impact loading. The measured values of this quantity for all five materials tested are shown in Table 2 and illustrated in Figure 9.

Again, it can be seen that the SP material (specimen 3) exhibited the highest impact fracture work ($W = 2.7\text{ J}$), confirming its superior performance over the other reinforcement materials. This leading position is further maintained in terms of mean values; with a mean impact fracture work of $W = 2.1\text{ J}$ for the SP material, the mean values of the SG, S/SPVA, and SA materials reach only 67%, 57%, and 52% of this figure, respectively. This demonstrates their increased brittleness. Interestingly, the base reinforcement (S), despite its low impact fracture work, exhibited a higher impact fracture initiation toughness than the SPVA and SA reinforcements. Although these two reinforcement materials exhibited lower dynamic fracture toughness values compared to the reference material S, they may demonstrate enhanced performance under ballistic and blast load, represented by reduced scabbing, and in the case of SPVA, also a significantly enhanced heat resistance [10].

3. DISCUSSION

Impact tension tests on specially designed specimens, made from five fibre-reinforced concrete mixtures with different types of fibre reinforcement, showed that the highest peak load value was exhibited by the propylene fibre-reinforced concrete (SP). In order to obtain a complete picture of the fracture behaviour of the tested materials and to enable more meaningful comparisons between them, the peak loads were converted to the stress intensity factor K_{I_d} – dynamic fracture initiation toughness. As can be seen from Table 3 and Figures 3–7, the SP material demonstrated superior performance compared to the other reinforcement materials. The mean fracture toughness value for the SP material was $171.4\text{ kPam}^{0.5}$, which is almost 50% higher than the value for the second-highest performing material (SG) and by 93% higher than the value for the lowest performing material (SA). What is surprising is that two materials, SA and SPVA,

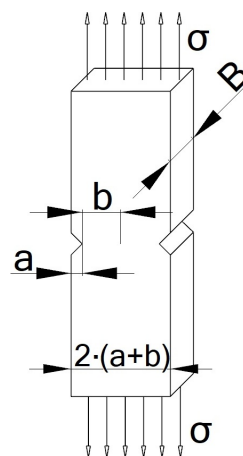


FIGURE 2. The double-edge notch test specimen.

Specimen	Material				
	S	SA	SPVA	SG	SP
1	58.0	96.2	72.2	104.6	180.8
2	111.8	71.9	113.5	87.5	165.2
3	79.1	55.9	87.2	155.0	211.1
4	152.7	130.2	115.0	119.9	128.5
Mean	100.4	88.6	97.0	116.8	171.4
St. deviation	35.8	28.0	18.1	24.9	29.8

TABLE 3. The stress intensity factors K_I ($\text{kPam}^{0.5}$).

exhibited lower dynamic fracture toughness than that of the base material (S). This means that not all fibre reinforcements added to the reinforced concrete (S) can lead to an increased dynamic initiation fracture toughness. This can be caused by either the fibre reinforcement material itself or its arrangement within the reinforced concrete. It is very likely that the reason for the high performance properties of the SP material was a highly uniform distribution of propylene fibres as well as their small diameter, unlike those of the other reinforcement materials. The specific shape parameters of the fibres (especially their low diameter) enable a more uniform distribution in the matrix and an increased number within the mass (at the same volume fraction), thereby improving fracture properties. Conversely, the lower performance of polyvinyl alcohol and aramid fibres can likely be attributed to their reduced dispersion level, with aramid fibres, in particular, exhibiting a tendency to remain in filamentous form, rather than being uniformly distributed within the matrix.

4. CONCLUSION

The medium-speed tensile tests conducted on fibre-reinforced concrete materials revealed the following findings:

- Using the appropriate secondary reinforcement can significantly improve the fracture behaviour of high-value concretes.

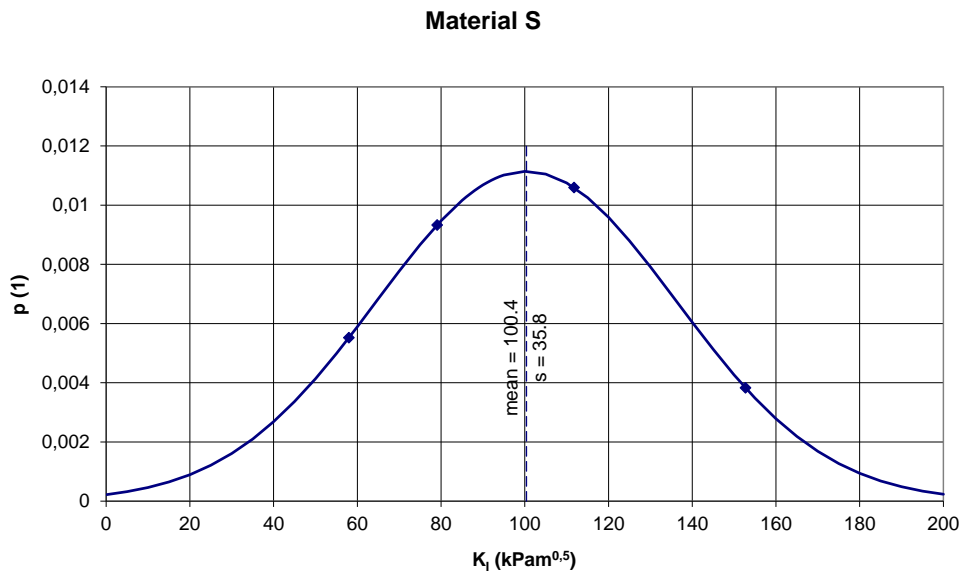


FIGURE 3. Probability density distribution of the stress intensity factor for S specimens.

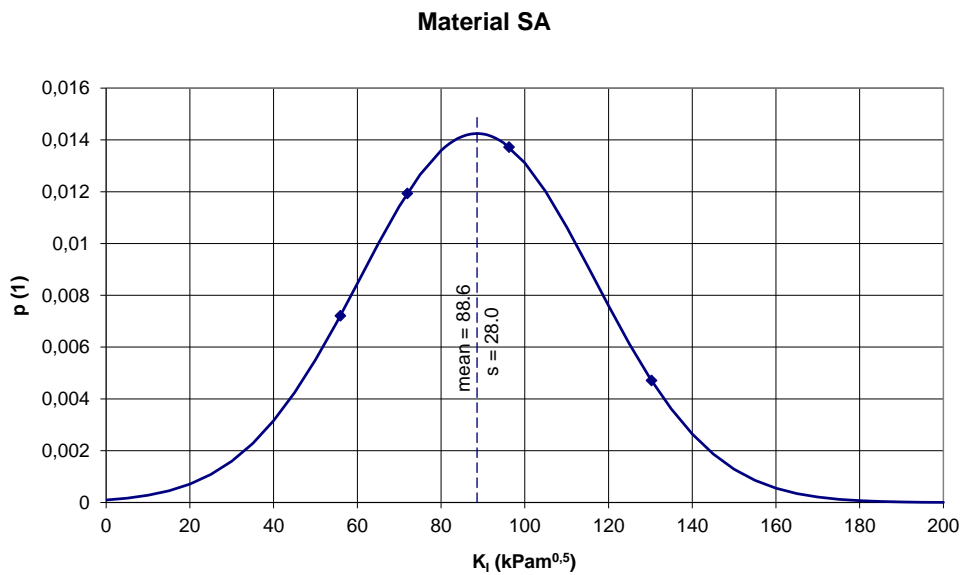


FIGURE 4. Probability density distribution of the stress intensity factor for SA specimens.

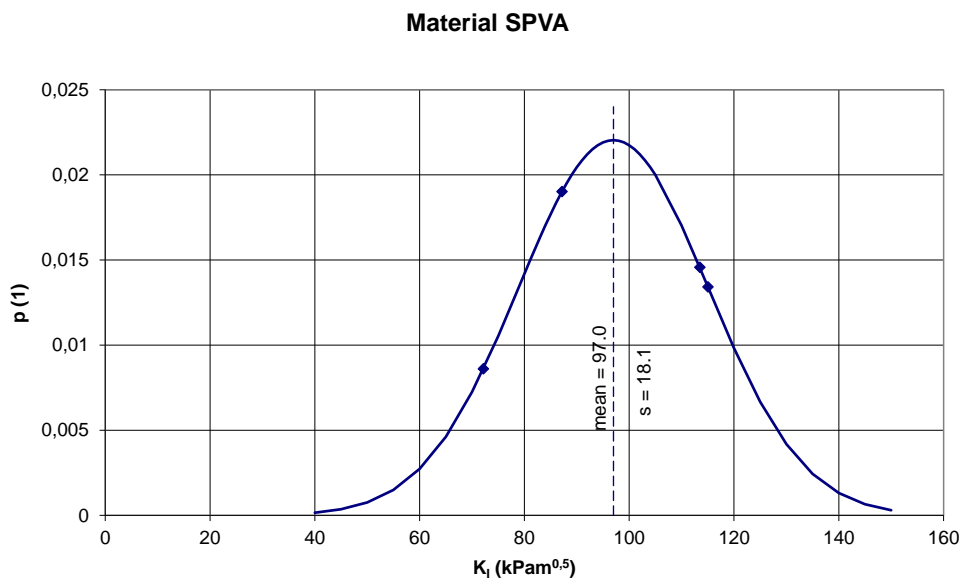


FIGURE 5. Probability density distribution of the stress intensity factor for SPVA specimens.

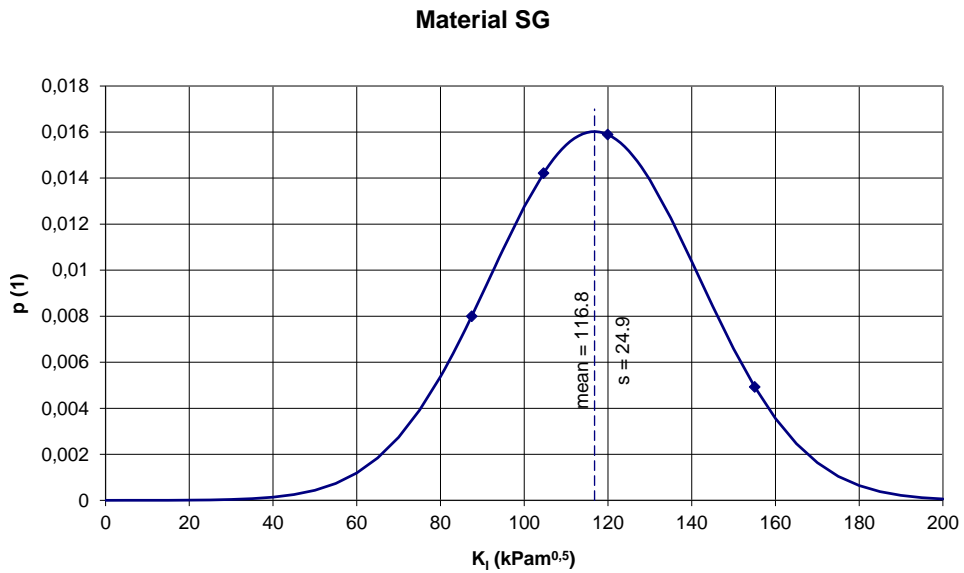


FIGURE 6. Probability density distribution of the stress intensity factor for SG specimens.

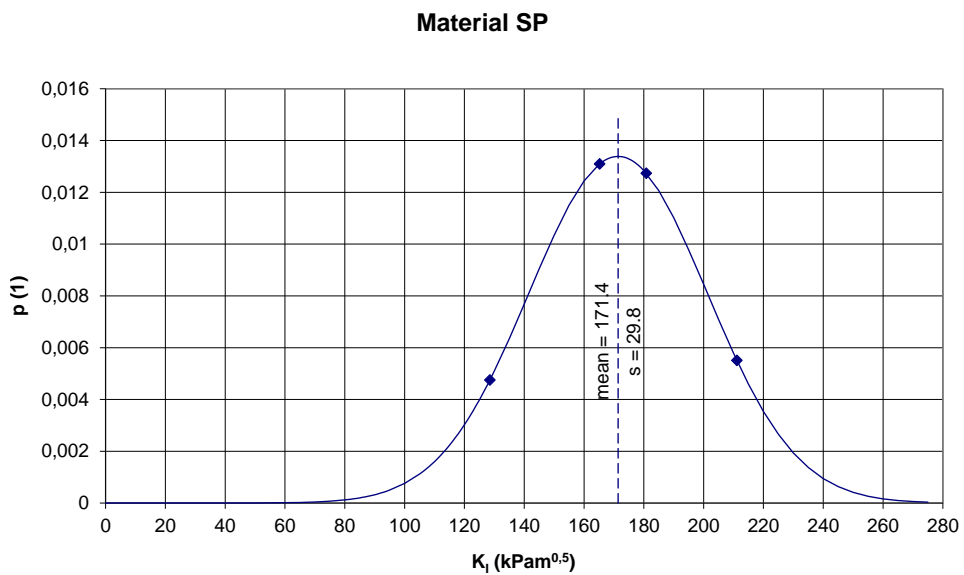


FIGURE 7. Probability density distribution of the stress intensity factor for SP specimens.

Summary diagram

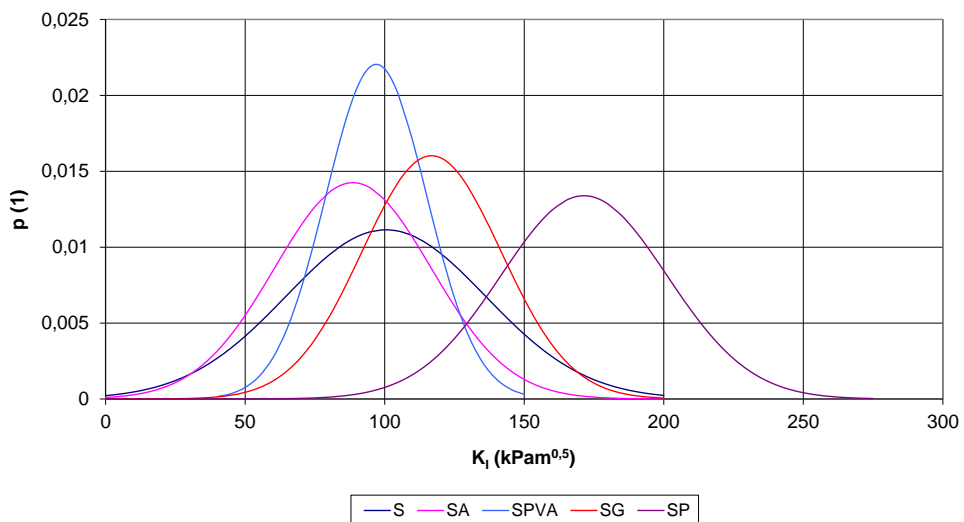


FIGURE 8. Probability density distribution of the stress intensity factor for all specimens.

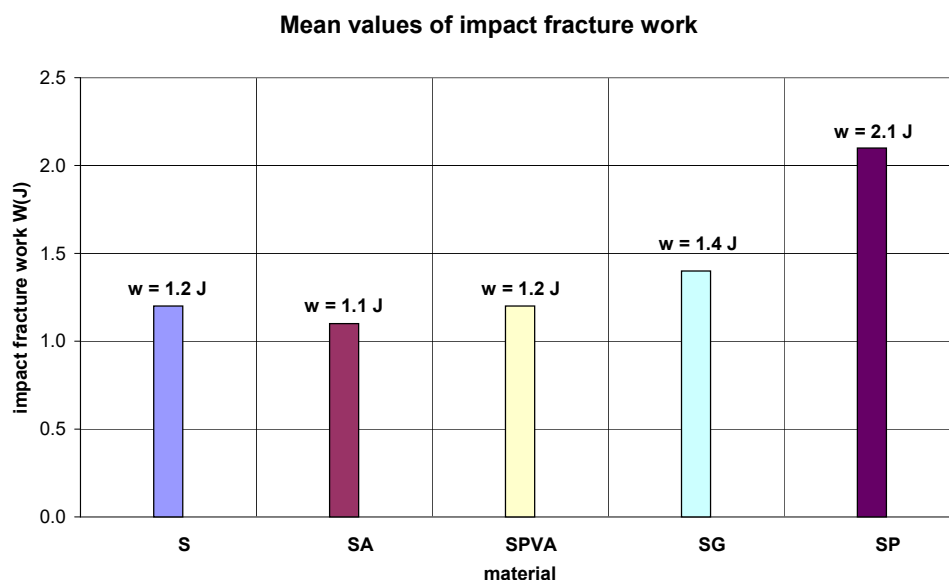


FIGURE 9. Mean values of the impact fracture work for individual tested materials.

- Adding polypropylene fibres to steel fibre-reinforced concrete significantly improved both dynamic fracture initiation toughness (K_{Id}) by over 70 % and impact fracture work by 75 %.
- Carbon fibres increased dynamic fracture initiation toughness (K_{Id}) by 16 % and impact fracture work by nearly 17 %.
- Neither polyvinyl alcohol nor aramid fibres improved dynamic fracture initiation toughness (K_{Id}) or impact fracture work.
- The uniform dispersion of fibre reinforcements (propylene) in the base material resulted in higher dynamic fracture initiation toughness and impact fracture work values.

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