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The influence of aggregate type on the strength and elastic modulus of high strength concrete

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HIGHLIGHTS

- The coarse aggregate type has an apparently contradicting influence on strength and elastic modulus of HSC.
- Aggregate with higher strength and stiffness results in lower strength but higher elastic modulus of HSC.
- In contrast to compressive strength, tensile strength of concrete is not significantly affected by coarse aggregate type.

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ABSTRACT

This paper examines the influence of 2 common South African aggregate types on the compressive strength, split and flexural tensile strength and elastic modulus properties of high strength concrete. Two different aggregate types (Andesite and Granite) were used to produce concrete with target strengths ranging from 30 MPa to 120 MPa. Granite concrete was found to have a higher compressive strength, while the stiffer Andesite aggregate produced concrete with a significantly higher elastic modulus. An attempt is made to explain this phenomenon with fracture mechanic theories. No trend was identified for the influence of aggregate type on splitting and flexural tensile strength. The effectiveness of the SANS and EN elastic modulus prediction models was analysed against the test results and it was found that both prediction models accurately predicted elastic modulus values for the Andesite concrete, but produced far less accurate predictions for the Granite concrete.

1. Introduction

High strength concrete (HSC) has been used extensively around the world, but has only recently become popular in South Africa. This form of concrete allows for much smaller concrete cross-sections in members, resulting in lower volumes of concrete being required. There are obvious benefits associated with this pertaining to reductions in formwork, transportation, reinforcing and on-site handling costs as well as the further benefits of structural members with significantly reduced self-weights that occupy much less space. The high strength required for HSC relies heavily on achieving a very low water: binder ratio of below 0.4 [20]. This allows high strength to be achieved by reducing porosity, inhomogeneity and micro cracks in the cement paste [15]. This in turn will have a direct effect on other intrinsic properties such as, tensile split and flexural strength, elastic modulus, creep deformation and shrinkage. Parameters such as, cement type, supplementary cementitious materials, chemical admixtures and curing techniques have been identified as having an influence on these key properties of HSC. However, the influence of aggregate and in particular, coarse aggregate type must also be considered.

Longstanding studies by Aitcin and Mehta [2], Zhou et al. [21] and de Larrard and Belloc [9] agree on the influence of different aggregate types on concrete compressive strength, with stronger aggregate types increasing the overall strength of the concrete. This is further supported by studies done by Ezeldin and Aitcin [10], Özturan and Çeçen [16] and Beshr et al. [6] who not only highlight the direct relationship between aggregate strength and compressive strength, but also show that there is a similar relationship with respect to concrete tensile and flexural strength.

A more recent study by Kılıç et al. [12] and reviewed by Kovler and Roussel [13] examined the influence of aggregate type on the strength and abrasion characteristics of high strength silica fume concrete. Five different aggregate types (gabbro, basalt, quartzite, limestone and sandstone) were tested with the same mortar mix. It was found that the stronger gabbro aggregate concrete had the highest compressive and flexural tensile strength while the weakest sandstone aggregate concrete had the lowest compressive and

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flexural strength. This confirmed the direct relationship between aggregate compressive strength and the resulting concrete compressive and flexural strength. This is supported by findings by Ahmad and Alghamdi [1], who conducted an investigation to study the effect of two different types of coarse aggregates on the performance of concrete in terms of compressive strength, modulus of elasticity, and steel-corrosion penetration rate. It was found that the strength qualities of the aggregate control the strength properties of the concrete.

Uysal [18] investigated the influence of coarse aggregate type on mechanical properties of self-compacting concrete (SCC) and also concluded that greater concrete strength was achieved with the use of higher strength aggregates.

Another key finding from Kılıç et al. [12] was that concretes made with aggregates with a high compressive strength (gabbro and quartzite) had a lower compressive strength than the actual compressive strength of the aggregate itself, while the lower strength aggregate concrete (basalt, limestone and sandstone) had a very similar compressive strength to the compressive strength of the respective aggregate itself. These findings were attributed to the idea that the strength of concretes made with higher strength aggregates is limited by the strength of the mortar paste and not the strength of the aggregate itself.

The elastic modulus of concrete is directly proportional to the stiffness of the individual phases that form its composition and their interfacial characteristics [5]. Aggregate type therefore has a direct effect on the elastic properties of HSC and Ahmad and Alghamdi [1] have shown that the effect of aggregate type on elastic modulus of concrete is very significant. This is supported by Uysal [18], who showed that an increase in elastic modulus of the concrete was found when a higher stiffness aggregate was used.

Rashid et al. [17] compared 644 elastic modulus results for concretes made with various aggregate types from available literature. These results were plotted against compressive strength and it was concluded that the impact of aggregate type on the elastic modulus of concrete at various strengths was very pronounced, with lower stiffness aggregates such as sandstone producing concrete with a significantly lower elastic modulus for all concrete strengths.

It is therefore necessary to consider the effect of the presence of coarse aggregate inclusions on the 'localised' mechanisms involved with concrete failure. Chiaia et al. [8] explains how, in heterogeneous materials such as concrete, failure will generally occur along the weakest link. This weak link is commonly represented by the interfacial transition zone (ITZ) between two dissimilar materials. In the case of concrete, the ITZ between the (mortar or cement) matrix and the aggregate particle is considered to be the weakest element in the material. The material is most likely to fail at the location with the highest stress relative to the interface strength. These higher stresses are located where two different materials with different elastic properties meet, at the interface between the matrix and the aggregate, resulting in stress concentrations. These stress concentrations play a key role in concrete fracture and failure.

Giaccio and Zerbino [11] describe how coarse aggregate particles arrest failure crack growth, producing meandering and branching cracks. This influence of coarse aggregate on crack propagation is dependent on aggregate characteristics such as surface texture, shape and stiffness. As previously highlighted, the difference in elastic properties of the matrix and the aggregate will have a profound influence on concrete failure. Giaccio and Zerbino [11] suggest that aggregate surface texture is one of the most important factors that affect matrix–aggregate bond strength, with rougher aggregates having superior bonds.

The concept of strain softening prior to failure of concrete must also be considered and involves the formation and nucleation of microcracks at these stress concentration zones and pre-existing microdefects which become "attractors" for the subsequent macrocracking development [8,19]. The process of macrocracking failure is characterised by the growth and expansion of interfacial cracking through the matrix. During the strain softening stage, this macrocracking will remain discontinuous until complete cracking failure is observed when macrocracking becomes continuous through the matrix. Strain softening can therefore improve the performance of concrete and directly influence the fracture energy required for failure. Fracture energy is described by Wittmann [19] as the specific energy required for cracking to occur.

However, studies by Wittmann [19] and Kovler and Bentur [14] found that the energy consuming cracking failure (strain softening) in normal strength concrete (NC) was not observed in the cracking of high strength concrete (HSC). Due to the increased strength of the matrix associated with HSC, crack formations were observed to run through the inclusions (aggregate) and form a plane similar to that observed for the failure of fine mortars. It was deduced that mechanisms of mechanical interaction (strain softening) between the inclusions and the HSC matrix were minimal, resulting in the more brittle failure of the HSC around the stress concentrations.

Another reason for the more brittle fracture process of HSC, compared to NC may be the consumption of Portlandite in the puzzolanic reaction in concretes using silica fume, which results in a better bond between aggregate and cement paste. As a consequence, the interface transition zone, often considered being the weak link in the concrete matrix and significantly contributing to the strain softening phenomenon, is strengthened.

This paper represents the results of a laboratory investigation that aimed to study the effect of two different aggregate types (Andesite and Granite) on the compressive strength, splitting tensile strength and elastic modulus of high strength concrete. Results show that aggregate type has a significant influence on concrete properties which is not always considered in conventional views and prediction models.

2. Experimental details

2.1. Mix design and curing

Four mixes of varying target strengths were developed that would be tested using Andesite and Granite fine and coarse aggregate (Table 1). The 90 and 120 MPa mix designs were based on mix designs from North America, developed by Burg and Ost [7], and perfected using a number of trial mixes. These would be compared to 60 and 30 MPa mixes. This would allow for comparisons to be made between the HSC mixes and normal concrete (NC) mixes.

The coarse aggregate content was kept the same to ensure an effective comparison. Silica fume was added to all of the mix designs, replacing roughly 10% of the cement content. Sika ViscoCrete – 10 superplasticiser was used for the 90 and 120 MPa mixes and Sikament – NN liquid superplasticiser was used for the 60 MPa mixes.

Two types of coarse and fine aggregates were used for the investigation mix designs from sources in the Gauteng Province and the Western Cape Province of South Africa. The coarse aggregate type from the Gauteng source is 19 mm Andesite. The aggregate is very angular in shape. The fine aggregate is from the same quarry and is crusher sand made from the same Andesite deposit. Alexander et al. [4] describes how Andesite develops an excellent bond with Portland Cement (PC) and enhances the fracture toughness of the paste-rock composite. Andesite has a relative density RD of 2.91, a stiffness factor (Ko) of ±26 GPa and an elastic modulus of ±81 GPa [3].

The coarse aggregate type from the Western Cape source is a 19 mm Granite and is also very angular in shape. Again the fine