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Misconceptions around compressive strength of cementitious repair materials for structural repair

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Abstract

Compressive strength is a critical parameter in the design and construction of reinforced concrete elements. It is a quick and cost-effective test, making it an attractive feature for quality control during construction. While higher strength classes indicate higher structural capacity, compressive strengths higher than that required at the ultimate limit state have no structural benefit and may even reduce sustainability, increase costs and lead to cracking. This paper summarizes research on compressive strength and its influence on concrete repair conducted by the Concrete Materials and Structural Integrity Research Unit at the University of Cape Town. The studies showed that a higher compressive strength has a higher tendency to crack under restrained shrinkage, and high-strength mortars do not structurally contribute to repaired members subjected to axial compressive loads in the long term. The paper concludes by recommending that upper limits on compressive strength be placed in repair standards and specifications and that greater attention be paid to parameters that influence crack sensitivity, particularly shrinkage, to achieve more durable repairs.

Keywords: Keywords: Concrete Compressive Strength, Structural Repair Materials, Structural Design, Quality Control, Durability.

1. INTRODUCTION

Compressive strength is arguably the most important property of concrete due to its use as the main parameter for structural design and for quality control and conformity assessment of concrete during construction. Concrete is typically graded into various strength classes. A higher strength class indicates a higher structural capacity, i.e., the ability to withstand higher stress when loaded. This higher load-bearing capacity is often mistaken to be a sign of higher quality, with many structural engineers and contractors assuming that a higher-strength concrete yields superior structural performance or durability. A particular example is the structural repair of damaged concrete members, where the aim is to restore the load-carrying capacity of a damaged concrete member to or beyond its original state [1]. European standards on the performance characteristics of repair materials for structural repairs list compressive strength as one of the top requirements. However, these requirements are no more than arbitrary lower-bound limits that have led to the production of commercial products with incredibly high strengths that far exceed these lower limits [2]. Datasheets on these high-strength repair materials sometimes describe them as “high-performance” but only focus on compressive strength and give little information on other characteristics.

This paper discusses the role of compressive strength in the load-bearing behaviour of reinforced concrete (RC) members, highlighting its importance in the structural design process. Subsequently, the rationale for using compressive strength as a parameter for quality control and conformity assessment is laid out, which helps to explain how compressive strength has developed into a general quality label for concrete. A summary of research on compressive strength and its influence on concrete repair conducted by the Concrete Materials and Structural Integrity Research Unit at the University of Cape Town is then presented, which shows that a higher compressive strength in repair mortars not only provides no additional benefit but reduces the repairs’ performance. Practical measures aimed at attaining more durable repairs are also presented.

2. COMPRESSIVE STRENGTH IN STRUCTURAL DESIGN AND QUALITY CONTROL

In the structural design of RC elements, concrete compressive strength is required to model and analyse the structure’s load-bearing capacity at the ultimate limit state (ULS). At ULS, structural optimisation of a RC cross-section aims at the reinforcing steel yielding as the concrete fails under compression, resulting in optimum use of material resources. Notably, from a structural engineering point of view, the concrete compressive strength is only needed for this imaginary moment in the lifetime of a structure, i.e. structural failure under a theoretical maximum load. In practice, conservative assumptions for selecting ultimate loads coupled with a range of material and structural safety factors should prevent the concrete from ever being exposed to stresses remotely close to the ultimate strength. For the expected everyday loads, which in structural design are considered for the Serviceability Limit State (SLS) and include the self-weight of the structure and conservatively assumed live loads, the concrete is expected to experience compressive stress levels around 30% of its compressive strength. Therefore, the ultimate compressive strength is irrelevant to the load-bearing capacity of a structure subjected to realistic everyday loads. The only practical effect of increased compressive strength is the associated increase in the concrete’s elastic modulus and reduction in creep, both of which may assist in reducing load-induced deformations, such as deflections in suspended beams or slabs. However, a desired reduction in deformation can more effectively be attained by other means, like an increase in the cross-sectional dimensions. Therefore, specifying and constructing concrete structures with a higher concrete strength than that used in the structural design for the ULS has no real added benefit for the load-bearing behaviour of the structure.

Concrete mix designs and specifications are typically based on achieving the required characteristic design strength, with the associated quality control measure being compressive strength testing at 28 days. Thus, while compressive strength is a necessary structural parameter for ULS design, it also serves as a quality control parameter due to its ease and cost-effectiveness of measurement. The assumption that higher strength equates to superior quality can be misleading, though, as concrete with a higher strength than that required for ULS design provides no structural benefit and may increase costs and reduce sustainability due to the need for a higher cement content. Higher strength can also result in lower workability, reduced bleeding, increased hydration heat development, increased brittleness, and increased risks of Alkali Aggregate Reaction and drying shrinkage cracking. The effects of higher concrete strength on the overall increased risk of cracking are significant, as cracking of the concrete cover depth, which protects the embedded steel reinforcement from corrosive agents, can significantly reduce the durability of concrete structures.

3. THE CORRELATION BETWEEN CRACKING AND COMPRESSIVE STRENGTH IN REPAIR MATERIALS

One of the main aspects impairing the performance of cementitious repair materials is cracking due to restrained shrinkage, which may result in reduced bond strength between the repair material and substrate and reduced durability due to the increased ingress of deleterious agents into the repaired structure.

The relationship between compressive strength and shrinkage cracking tendency was investigated for a total of 40 different concrete repair mortars with strengths ranging from around 10 – 60 MPa [3]. The mortars were manufactured with different cementitious binder types and contents, water/binder ratios, chemical admixtures, mineral additives, water contents, aggregate combinations, and curing conditions. The tendency to crack was investigated with the ring test according to AASHTO and ASTM, which provides a comparative evaluation of the sensitivity of the cementitious material to crack under the effect of restrained shrinkage and is a helpful tool for the optimization of material performance concerning selected specimen parameters, compressive strength in this case. Figure 1 shows the compressive strength and age at cracking for the 40 different mortars tested[1].

It can be observed in the figure that, while there is a scatter in results, an inverse relationship exists between the age at cracking and compressive strength, with a higher compressive strength generally increasing the tendency to crack. This phenomenon was also reported earlier by Dittmer and Beushausen [4]. Furthermore, it was observed that increasing the compressive strength at 28 days beyond approximately 35 MPa did not significantly change the age at cracking, pinpointing this strength as the “cracking threshold” in this research project. The results were owed to the correlation between stress and strain as expressed through Hooke’s Law. Increasing strength is generally accompanied by a corresponding increase in elastic modulus and a decrease in tensile creep and relaxation. With other characteristics constant, an increase in elastic modulus and a reduction in tensile creep and relaxation generate higher stresses when shrinkage deformations are restrained, consequently increasing the susceptibility of the cementitious material to cracking.

[1]Note that three specimens were tested for compressive strength and restrained shrinkage per a mix, respectively.

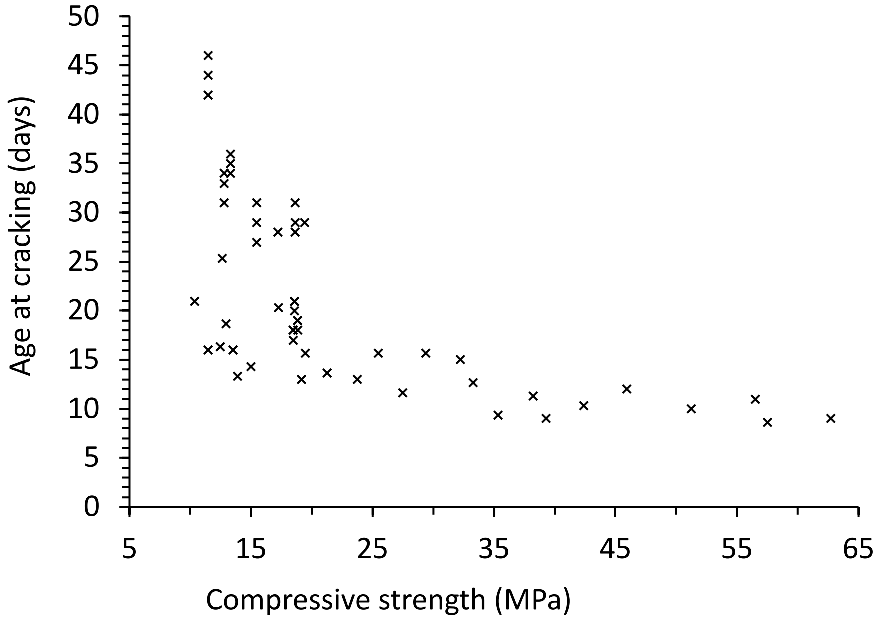

Figure 1: Age at cracking versus compressive strength at 28 days across test specimens [3].

4. STRUCTURAL EFFECTS OF COMPRESSIVE STRENGTH IN REPAIR MATERIALS

The notion for cementitious repair materials to have a high compressive strength is the perception that these materials can structurally contribute to the load-bearing capacity of repaired reinforced concrete members. While various studies have considered the ultimate contribution of repair materials to members under axial load states, few studies have focused on their long-term performance.

The long-term effects of high-strength cement-based repair materials on repaired members under compressive loads were investigated using an analytical model developed using Hooke's law and Euler-Bernoulli beam theory [5, 6]. The model makes various assumptions relating to uniform strain, load eccentricities, and the transfer of stresses between the concrete substrate and repair material. Externally applied loads and characteristics of the concrete substrate and repair material serve as inputs to the model. These characteristics are compressive strength, elastic modulus, drying shrinkage, and specific creep, which are time-dependent. However, since concrete repairs are typically conducted on aged concrete structures, the concrete substrate's drying shrinkage and creep characteristics would be negligible and thus were not considered. One-day time step increments were used to monitor the influence of the repair material properties on the repaired member over time.

The analytical problem considered an unreinforced concrete square column repaired with high-strength cement-based concrete. The square column had a 500 × 500 mm cross-section, with the repair spanning the columns' entire width and going to a depth of 100 mm, making up 20% of the columns' cross-sectional area (see Figure 2). Damage was assumed to be concentrated to where the repairs were conducted, an example of which could be poor workmanship (e.g. honeycombing) not detected during construction. The repair material selected was a high-strength cement-based concrete made of a SikaGrout-212 grout and 9.5 mm Greywacke stone aggregate. The dry-mix content of the SikaGrout-212 grout was 1645 kg/m^3, while the stone content was 461 kg/m^3. A water/binder ratio of 0.14 was used (as per the material datasheet) to yield a water content of 230 kg/m^3. It was assumed that all loads were removed before the repair and that the only form of strain recovery in the substrate over the repair period was elastic. One day after the repair, an axial compressive load of 25 MPa was applied and maintained.

Compressive strength, elastic modulus, shrinkage, and creep tests were conducted on the repair material at various ages, while the concrete substrate was chosen to have an elastic modulus of 25 GPa and compressive strength of 50 MPa. The high-strength cement-based concrete had compressive strengths of 42 and 77 MPa and an elastic modulus of 25.5 and 28.5 GPa at 1 and 28 days of age, respectively. Its drying shrinkage and creep were tested at 1 day of age and exposed to a temperature and relative humidity of 22 ± 1°C and 55 ± 5%, respectively. After 90 days, the drying shrinkage strain and specific creep of the high-strength concrete were 340 µ-ε and 120 µ-ε/MPa, respectively, with 89% of the drying shrinkage strain measured after 13 days. The model results in Figure B showed that while the stress in the repair was equivalent to the concrete substrate when loaded, it dropped significantly in the following days, with only 20% of its original stress remaining in the repair after eight days. Conversely, due to this drop in stress, the stress in the substrate increased by 20% in the first eight days. After 14 days of loading, the stress in the repair was below 2.5 MPa, while the stress in the substrate concrete was slightly above 30 MPa.

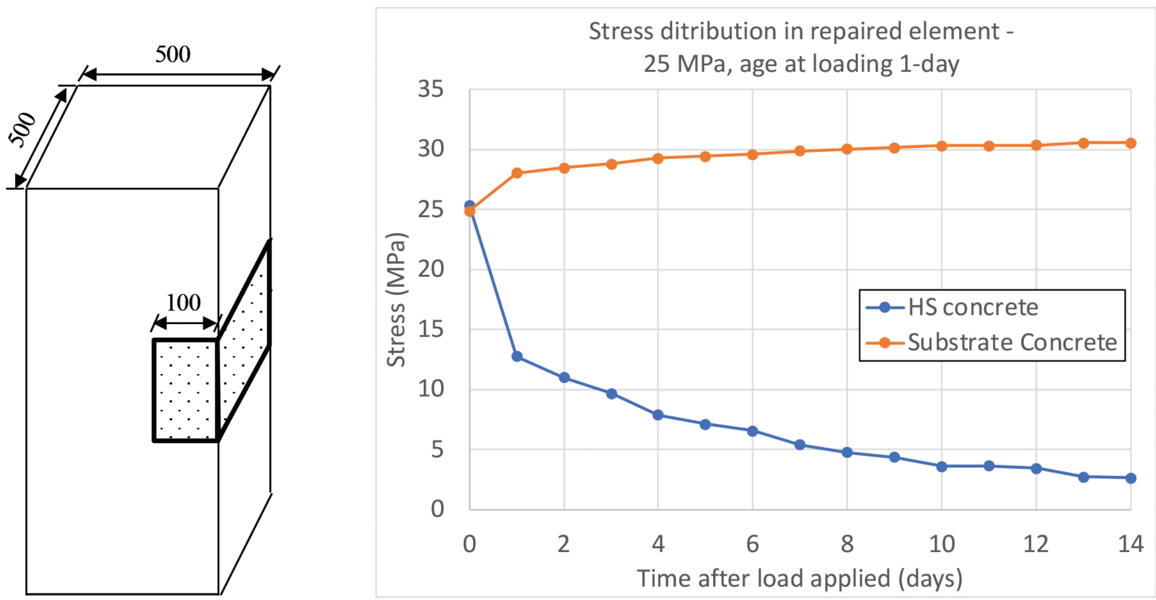

Figure 2: Repair geometry and stress outputs from analytical model over time [5].

The equivalences in stress distribution between the repair and substrate on the day of loading (one day after repair) were owed to the similarities in the elastic moduli. However, as shrinkage and creep develop in the repair material, the repair stress reduces and is transferred to the concrete substrate. This stress reduction results in the repairs' contribution to resisting the externally applied loads reducing over time, leaving the substrate concrete to withstand these surplus loads. The repair is effectively then no longer contributing to the load-bearing capacity of the column after 14 days, despite the high strength values of the repair material.

5. MORE FOCUS ON DURABILITY THAN COMPRESSIVE STRENGTH IN REPAIR MATERIALS

The studies above illustrate that the common belief that high strength is a sign of high quality in concrete repair materials is misleading. Not only do these high strengths increase the susceptibility of a cementitious material to crack, but they offer no benefit in contributing to the load-bearing capacity of a repaired member under axial compressive loads. Instead, more focus should be placed on improving the durability of repairs by limiting the repair materials' susceptibility to cracking. Such remarks have been echoed by Tilly [7] and Vaysburd et al. [8], who noted an undue emphasis on strength and not enough on durability.

A simple measure is to put upper bound limits to compressive strength values in standards and specifications for materials used in repair, where an acceptable range is defined based on the requirements of the repair. Such an approach would reduce the use of excessively high-strength repair materials, which have been shown to be highly susceptible to cracking.

Material properties that influence crack sensitivity should also be considered. An example of this is given in Table 1, which shows how influential a parameter is towards crack sensitivity. One parameter listed as a major factor that has been raised in the studies above is shrinkage. Despite its importance, very little attention is given to this property. Vaysburd et al. [8] found that of the 120 North American repair projects reviewed, not a single specification gave a limitation on shrinkage. Commercial products have also had an influence, often labelling themselves as "non-shrinking" or "shrinkage-compensating". However, research at times has shown this not to be the case and that some of these materials could be more classified as low shrinkage than anything else [9, 10].

Greater emphasis on shrinkage must thus be placed if repairs are to be more durable. Specifying strain limits and, more importantly, the age and exposure conditions are critical steps in this regard. However, further steps towards evaluating the repair material's sensitivity to cracking must also be considered. A combination of free and restrained shrinkage tests, such as the ring test [11], are considered suitable for evaluating repair mortars. The free shrinkage test observes the amount of shrinkage a repair mortar undergoes for a given exposure condition, while the restrained shrinkage test evaluates its tendency to crack when this shrinkage is restrained.

Table 1: Material properties that influence the repair materials sensitivity to cracking [12].

Parameter	**Effect**		
	Major	**Moderate**	**Minor**
Drying shrinkage	x		
Modulus of elasticity	x		
Creep		x	
Compressive strength	x		
Early strength	x		
Paste content	x		
Cement content and type	x		
Aggregate content, type and size	x		
Coefficient of thermal expansion			x
Water to cementitious materials ratio			x
Accelerating admixtures	x		
Plasticizers		x	
Silica fume	x		
Fly ash		x	
Slag		x	
Water content	x		
Slump (within typical ranges)			x

6. CONCLUDING REMARKS

This paper presented a summary of research conducted by the Concrete Materials and Structural Integrity Research Unit at the University of Cape Town on compressive strength and its influence on concrete repair. The studies showed that repair mortars with a higher compressive strength generally have a significantly higher tendency to crack under the effects of restrained shrinkage. Furthermore, in cases where repairs are expected to structurally contribute, the developed analytical model revealed that the contribution of high-strength repair mortars rapidly declines in the first days of loading. More emphasis should thus be placed on the repair materials' durability and limiting its susceptibility to cracking than its compressive strength. Placing upper limits to the compressive strength in repair standards and specifications, while placing greater emphasis on shrinkage and crack sensitivity of repair materials are seen as simple measures to reduce the use of excessively high-strength repair materials and attain more durable repairs.

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