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The effect of coarse aggregate content and size on the age at cracking of bonded concrete overlays subjected to restrained deformation

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HIGHLIGHTS

- Coarse aggregate content has a near-linear relationship with cracking age in overlays.
- Coarse aggregate size has a significant effect on overlay cracking.
- An analytical model for overlay cracking, depending on aggregate content is proposed.

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ABSTRACT

The influence of coarse aggregate content and size on cracking of bonded concrete overlays was investigated using the ring test. Specimen parameters included 4 different coarse aggregate contents, 2 aggregate sizes and 3 strength grades. Test results for relevant time-dependent material properties such as drying shrinkage, tensile strength, tensile relaxation and elastic modulus were used to predict the time to first cracking using previously established analytical models. Increases in both coarse aggregate volume content and size were shown to significantly prolong the time to first cracking in the ring test, while an inverse relationship was observed for crack intensity. The analytical model was found to be ineffective in detecting the influence of coarse aggregate content and size on the cracking behavior of bonded overlays. This was ascribed to the model's inability to account for aggregate-related differences in strain softening and fracture mechanisms on a micro scale.

1. Introduction

Internationally, a growing need exists for improved methods and understanding of concrete repair and retrofitting technology. This is the result of a number of different factors that result in existing concrete structures not reaching their intended service lives [1–3]. The economic implications of concrete repairs, which were often not accounted for in the original design, can have a profound effect on the continued feasibility and upkeep of major civil engineering, commercial and housing structures [1,3]. A major related problem links to the circumstance that currently only very limited design methods and material specifications are available for concrete repair, with many of the prevailing mechanisms of repair failure not being well understood.

The bonded concrete overlay repair technique is the most commonly used method for concrete repair and is used extensively around the world [4]. The method, which involves casting a new layer of concrete over an existing substrate, can be used for structural repairs where the overlay is loaded and fulfils a structural role or simply for non-structural repairs to cover and protect exposed reinforcing steel or damaged concrete [2,4,5]. The concept of differential volume changes between the substrate and overlay is based on the notion that the overlay is subjected to shrinkage and thermal movement, while the substrate's movements are usually completed or minimal. Bonded overlay deformation is therefore restrained at the interface to the substrate, resulting in tensile stresses, which in many cases is linked to overlay cracking [1–3,5–7].

A number of time-dependent overlay material properties have been identified as contributing directly to overlay cracking characteristics, namely: shrinkage, tensile strength, tensile relaxation and elastic modulus. Researchers suggest that differential shrinkage, and in particular drying shrinkage, is considered the most critical influencing factor that contributes to differential volume changes and directly affect the cracking failure of bonded concrete overlay repairs [7–11,18,19,23]. In contrast, tensile relaxation has been identified as a key property that can help to alleviate some of the

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tensile stress induced by overlay shrinkage [7,18,19]. Tensile stresses due to restrained deformations are also significantly affected by the elastic properties of the overlay material, with an increase in repair material stiffness resulting in greater stresses [2,6,7].

The inclusion of coarse aggregates in concrete has been shown to have a significant influence on individual key material properties that impact overlay cracking as indicated above. Coarse aggregate volume, size, stiffness, shape and grading influence concrete shrinkage through the mechanisms of dilution and restraint, and therefore have a direct influence on stress-producing shrinkage deformations [12,13]. The elastic properties of coarse aggregates have further been shown to directly influence the elastic properties of concrete, which is particularly related to coarse aggregate size and content [13]. Considering material properties only, it can thus be assumed that an increase in coarse aggregate content in bonded overlays has the positive effect of reducing shrinkage and related tensile stresses. However, this is combined with the negative effect of increasing aggregate content which increases the overlay's elastic modulus and the related stresses from deformation restraint.

The effect of coarse aggregate on tensile relaxation has been shown to be more complex, with Alexander and Mindess [13] suggesting that in a larger 'global' context, the function of dilution and restraint due to coarse aggregate has a direct influence on tensile relaxation. However, in a more 'local' context, the effect of microcracking within the interfacial transition zone (ITZ) between the aggregate and the cement paste has been shown to result in increased stress relaxation [14].

In addition to the influence of aggregates on individual material properties, the inclusion of coarse aggregate particles on overlay cracking must also be considered on a 'local' scale around the actual location of cracking. This partly relates to the process of strain softening which involves the formation and nucleation of microcracks at stress concentration zones at the interface between the matrix and the aggregate inclusions [15,16]. The degree of strain softening will determine the specific fracture energy required for cracking to occur. Wittmann [16] and Hillerborg [17] have shown that fracture energy and strain softening are dependent on the length of crack propagation paths, and have been shown to increase with an increase in aggregate particle size and volume content.

The above sometimes contradictory effects of coarse aggregates on material properties that affect stress development in bonded concrete overlays subjected to restrained deformation warrant closer experimental and analytical research.

The ring test detailed in the AASHTO and ASTM standards [18] is the most widely used by researchers to evaluate the restrained shrinkage of repair materials. However, Bentur and Kovler [18] conclude that the ring test only provides a qualitative indication of the material cracking. Beushausen and Chilwesa [19] suggest that a more detailed and quantitative prediction of overlay cracking can be obtained by analyzing the key material properties affecting stress development as discussed above. An analytical model for the prediction of tensile stresses in bonded mortar overlays subjected to restrained deformation has been developed and successfully used by the second author [6,7,19,27]. While this model has shown to have an acceptable degree of accuracy for mortars, it had previously not been used to analyze overlays containing coarse aggregates.

The objectives of this study were twofold. Firstly, to experimentally evaluate the influence of coarse aggregate volume content and size on the individual key material properties known to affect overlay cracking, as well as testing the direct influence of coarse aggregate content and size on overlay cracking with the ring test. Secondly, to evaluate the accuracy of the previously developed analytical model in accounting for the influence of coarse aggregate content and size on the cracking of overlay materials. Comparing the predicted analytical outputs, which were based on the individually tested material properties, with the results obtained in the direct ring tests helped to achieve this objective. This assisted in determining if predictions based on individual material properties can account for 'local' fracture mechanisms and strain softening associated with the inclusion of coarse aggregate in bonded overlays.

2. Experimental details

2.1. Outline and approach

The influence of coarse aggregate volume content and size on key material properties that influence overlay cracking was investigated. This involved the individual measurement and testing of free drying shrinkage, tensile strength, tensile relaxation and elastic modulus. Tests were conducted on two self-designed concrete mixes and one commercial repair mix. Each of the mixes was cast with 4 different volume contents of coarse 19 mm aggregate. A further set of mixes was made using different contents of a smaller 9.5 mm coarse aggregate, to examine the influence of coarse aggregate size. This is discussed in more detail in later sections.

The mixes were further tested for cracking characteristics using the ring test, which included visual observation of the time to first cracking. Crack intensity was analyzed based on total crack area (in [mm^2]) measured 14 days after initial cracking.

The individual material properties that were measured in the experimental component of the study provided the inputs for the analytical model that was used to predict the time to failure of the different mixes. These predicted outputs were then evaluated and compared with the direct test results of the ring tests.

2.2. Mix designs

Two self-designed overlay mixes were used with water/binder ratios of 0.45 and 0.60, referred to as LM45 and LM60 respectively. The mixes were made using a CEM II-42.5 (containing fly ash) and a 50/50 combination of siliceous pit sand and dune sand (both 0–2 mm). A liquid superplasticiser was used where required to achieve the required design workability, which was set at a slump of 50 ± 20 mm.

In addition, a commercially available repair product was included in the study to enhance the relevance of the investigation to current practice in the concrete repair industry. This commercial mortar, in the following referred to as CM, is marketed as a high performance cementitious grout that can be used for concrete overlays and general repair purposes. The mortar was mixed in accordance with the specifications provided by the manufacturer. Due to its proprietary nature, no details were provided with regard to the composition of the CM.

All of the 3 basic mixes (LM 45, LM 60, and CM) were manufactured with 4 different volume contents of coarse aggregates (0%, 25%, 35%, and 45%), using a 19 mm maximum size Greywacke stone. In addition, all LM 60 mixes were also manufactured with a 9.5 mm maximum size of the same Greywacke stone, resulting in a total of 15 different overlay mixes as detailed in Table 1.

Aggregate grading has been shown in the literature to have a direct influence on shrinkage, creep, tensile strength, tensile relaxation and plastic properties of concrete [12,13]. A graded coarse aggregate, based on grading curves in the ASTM C33 code, was therefore used for both the 19 mm and 9.5 mm stone (Figs. 1 and 2).

2.3. Environmental conditions and curing

Specimens were kept in the moulds for 24 h after casting and subsequently cured for an additional 6 days using wet hessian and plastic sheets. On completion of moist curing at 7 days of age, all specimens except the tensile relaxation specimens were exposed to and tested at controlled environmental conditions of 25 ± 2 °C and 55 ± 5% RH. The tensile relaxation specimens, which were tested outside the controlled environment for a test duration of 48 h, were coated in a wax layer to prevent moisture loss during that time.

2.4. Experimental test methods

2.4.1. Drying shrinkage

Free drying shrinkage strain were tested using 100 × 100 × 200 mm prism specimens. Two pairs of Demec strain targets were attached to the specimens on opposite sides at 100 mm gauge lengths. A Demec strain extensometer with a 100 mm gauge length was used to measure shrinkage strains, which was recorded as the mean value obtained from 3 separate specimens per mix (i.e. from a total of 6 measurement locations). Shrinkage strains were measured several times a week over a total period of 56 days.