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Statistical relationship between mix properties and the interfacial transition zone around embedded rebar

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ABSTRACT

The relationship between concrete mix properties and the properties of the interfacial transition zone (ITZ) formed around embedded rebar was investigated. Multiple samples of various mix compositions and bar orientations were prepared so as to represent common concrete technology. Water-to-cement ratios varied from 0.40 to 0.65 and powder (cement + limestone filler) contents ranged from 362 kg/m^3 to 564 kg/m^3. Over 1300 BSE images of the steel–concrete interface were taken and analyzed automatically. Statistical methods were used to identify correlations between ITZ properties and mix composition or fresh mix properties.

A single large void was identified beneath all horizontal bars regardless of concrete composition. The ITZ around vertical bars was more uniform and extended around the entire rebar. No clear relationship was found between ITZ thickness and mix composition or fresh mix properties for either vertical or horizontal bar orientations. The degree of ITZ variability beneath horizontal bars clearly depends, however, on the bleeding properties of the mix. The distance from steel surface to the closest concrete solid, which influences the chemistry over the surface of the steel, is affected by precipitation of hydration products in horizontal bars, but not by mix composition.

1. Introduction

The interfacial transition zone (ITZ) in concrete is a phenomenon whereby properties of the cement paste adjacent to a solid boundary, such as aggregate or rebar, deviate from those observed in the bulk paste [1]. The ITZ between steel rebar and the surrounding concrete influences the mechanical behavior [2] and durability [3–5] of reinforced concrete structures. Most ITZ studies investigated the interface between cement paste and aggregates. These studies found higher porosity in proximity to the aggregate surface than in the bulk paste. The width of the ITZ around aggregates was quantified and found to extend up to 100 μm [6]. Liao [6] also found that during the hydration of cement, calcium hydroxide and secondary cementitious compounds precipitate within the pores of the ITZ and reduce its porosity. This porosity is assumed to be the result of poor compaction of cement grain along the interface due to the wall effect and micro-bleeding beneath the aggregate [7]. During the first two months of hydration, the width of the high porosity region decreases from 100 μm to about 15 μm [6], with the formation of different hydration products at each age, a phenomenon known as preferential precipitation [1,6,8,9].

The ITZ around aggregates is known to be controlled by changing the particle grading to include particles smaller than the cement grain. This leads to a denser ITZ, due to reduction of the wall effect, and also changes the concrete's rheological properties, especially its bleeding [10]. Decreasing the water/cement (w/c) ratio reduces ITZ porosity around aggregates; according to [11], when the w/c ratio is 0.40 or less, ITZ porosity equals that of the bulk. Aggregate size also influences the porosity around the aggregate: the larger the aggregate, the higher the porosity [11]. The above observations were made for aggregates that were much smaller than steel rebar and that were subjected to strong shear forces that develop while mixing them with the cement paste.

Since the rebar is at rest in the form during casting, the ITZ around it differs from the ITZ around aggregate and was found to have different properties [7,12,13]. Some investigators emphasized the differences between the ITZ formed around vertical bars versus horizontal bars. Specifically, the ITZ formed around vertical rebar tends to be uniform and dense, whereas that formed around horizontal rebar has two distinct zones: an upper zone, above the rebar, that is relatively dense, and a lower zone, beneath the rebar, that is relatively large and porous, often consisting of a single, large

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pore. Such differences in the ITZ also lead to micro-level differences in the mechanical properties of the paste beneath and above the rebar [2]. The differences between the areas above and below the rebar are less pronounced in self-consolidating concrete (SCC) [2]. Consolidation and internal bleeding (upward movement of water over solid particles that move downward during the consolidation of fresh concrete) were indicated as the cause of this difference [2,3,7,14]. Despite the broad agreement regarding the causes of this phenomenon, little information is available on the effect of concrete ingredients or fresh mix properties on the properties of this zone.

It appears, however, that ITZ properties are influenced by the fresh mix properties, which in turn are affected by the mix composition. Water and high-range water-reducing admixtures both decrease the concrete's plastic viscosity and yield stress [15]. Increasing the water/binder (w/b) ratio reduces plastic viscosity and increases bleeding [16]. Limestone powder, plasticizers, viscosity modifying agents and w/b ratio were found to have a strong influence on grout bleeding [16]. Replacing cement with limestone filler is associated with increased bleeding. Plasticizer and viscosity agents exhibited opposite effects: at low w/b ratios, increased plasticizer content increased bleeding, while increasing viscosity agent content reduced bleeding. Opposite effects were found at high w/b ratios [16].

The spatial nature of the ITZ was investigated mainly by analyzing a relatively small number of images, taken along [4] or across [7,17] the steel–concrete interface. Diamond [18] emphasized the need for a large number of measurements, because "the variation within a given tier around the periphery of a grain are often as great as, or greater than, the mean ITZ effects as customarily measured". This observation by Diamond [18] and by others [19,20] led some authors to emphasize the importance of automated image analysis in quantitative research [19,20]. Automated image analysis offers the ability to analyze a large number of images in a way that is unbiased by human perception, yielding reliable information that can be analyzed statistically.

A vast amount of work has been done to understand the nature of ITZ around aggregates, and some work has been done to investigate the ITZ around steel rebar. Nevertheless, very few of the works were quantitative, and the porosity around steel rebar has yet to be correlated with mix properties of regular concrete. This paper presents part of a comprehensive study aimed at identifying the influence of ITZ properties on steel corrosion and recognizing the major parameters that influence the formation of ITZ around reinforcing bars in commonly used concrete technology. It offers an unbiased statistical examination of the data and correlations between the mix properties and the ITZ properties, which are relevant for corrosion susceptibility. The relationships were determined using statistical methods to obtain reliable information, in view of Diamond's statement regarding the variability of ITZ properties [18]. Relationships between mix composition and ITZ properties were derived from automated image analyses of images taken around the entire perimeter of rebars for a large number of different mixes. ITZ properties were determined using an automated procedure. Over 1300 images of 16 different mix compositions and two rebar orientations were analyzed. Details of the automated image analysis developed for this study can be found in [21].

2. Methods

Sixteen different concrete mixes were produced so as to create varying ITZ properties using common concrete practice, i.e. workable concrete with good cohesiveness. Two series of mixes were prepared: (1) no filler and varying w/c ratios ranging from 0.40 to 0.65. Cement content ranged accordingly from 345 kg/m^3 to 527 kg/m^3; (2) constant w/c ratio of 0.45 or 0.52 with varying powder content. Powder content (cement, filler, and fines in the aggregates) ranged from 135 l/m^3 to 204 l/m^3. Powder content was calculated based on volume to account for the different specific gravity of the cement, filler, and fines. Water–powder (w/p) ratio ranged from 0.91 to 1.36 (by volume). Workability ranged from a slump of 80 mm to 185 mm. In addition a quasi-SCC mix was produced with the lowest w/p ratio, so as to investigate the influence of rheological properties of the extreme case but note that this mix does not represent a common concrete technology. It should be noted that a water-reducing agent (WRA) was used in various dosages to keep the concrete in workable state. One mix (w/c = 0.40) was cast twice on different days and served as an indication of our control over the concrete production process. Table 1 presents a list of mix compositions. All mixes were cast with rebar mounted in both horizontal and vertical positions so as to obtain different ITZ structures around the rebar, as described in [7].

ITZ properties were quantified using automated analysis of back-scattered electron (BSE) microscopy images, as described in [21]. Correlation coefficients were analyzed to reveal correlations between mix contents and properties and ITZ properties.

2.1. Materials

- *Cement:* CEM I complying with EN 197:2000.
- *Coarse aggregates:* crushed dolomite, 0–9.5 mm.

Table 1
Mix compositions per 1 m^3 of fresh concrete.

Mix	Water (kg)	Cement (kg)	Air[a] (l)	Coarse (kg)	Fine (kg)	Filler (kg)	WRA[b] (kg)	w/c (w/w)	w/p (v/v)
W40	211	527	20	1359	249	0	5.3	0.40	1.12
W40B2	211	525	23	1356	249	0	5.3	0.40	1.12
W45	207	475	22	1384	287	0	4.1	0.44	1.21
W45C04	211	468	13	1359	299	19	4.7	0.45	1.20
W45C08	221	491	22	1348	223	39	4.4	0.45	1.16
W45C12	224	496	18	1374	187	60	5.0	0.45	1.12
W45C16	213	473	19	1373	204	76	4.7	0.45	1.07
W45C20	212	470	19	1384	184	94	4.9	0.45	1.04
W50	199	428	18	1396	339	0	2.1	0.47	1.28
W52C08	218	419	5	1378	300	34	4.2	0.52	1.36
W52C12	214	411	15	1378	279	50	4.1	0.52	1.27
W52C17	205	393	0	1386	325	68	5.9	0.52	1.25
W52C54	179	345	9	1164	496	208	6.2	0.52	0.91
W55	210	381	13	1351	400	0	1.9	0.55	1.49
W60	221	367	9	1393	355	0	0.0	0.60	1.62
W65	235	362	6	1390	335	0	0.0	0.65	1.75

[a] Calculated.
[b] Polysulfonate-based water-reducing agent, except mix W52C54 where polycarboxylate-based water-reducing agent was used.