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On functional signatures of bare and coated formwork skin surfaces

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HIGHLIGHTS

- Correlation established between formwork skins signatures and their functionalities.
- Steel formwork skin and coated formwork skin were compared.
- The chemical signature was studied using the sessile drop method.
- Surface texture of formworks was taken into account to predict the particles trapping.
- Delamination of the oxide layer was studied by scratch testing and models.

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ABSTRACT

The sticking of the concrete on metallic formworks during building construction generates many concrete wall defects. Several solutions have been proposed, among which surface lubrication and polymeric coatings are commonly applied. In this paper, the main functional signatures of a steel formwork skin and a polymeric coating were determined to understand their effect on the concrete sticking. The topographical, chemical and mechanical signatures of the surfaces were characterized at near-surface regions. The top of the steel formwork a 10 μm-thick layer is constituted of two oxides each one having specific tribological properties. Adding the polymeric coating on the formwork skin surface lowers its surface tension, which lowers the sticking by reducing the wettability. Moreover, the smaller roughness of the coating limits the susceptibility of mechanical anchoring. Nevertheless, scratch testing suggests a short durability of the polymeric coating due to its weak resistance to abrasion.

1. Introduction

The vast majority of reinforced concrete walls are today built with formworks that maintain the poured concrete during its curing. The formworks are composed of a skin fastened on a rigid structure. Bare steel skins are largely common on construction sites for their sturdiness and their long life span. Nevertheless, the skin surface characteristics will be partially transferred to the cured concrete surface [1]. Subsequently, other skin materials such as wood, plywood, and polymeric coatings [1] are used for improving the concrete wall quality by modifying the superficial interactions between the concrete and the skin.

Superficial interactions with the skin initiate as soon as the concrete is poured through the formation of a boundary layer. This layer formed in the skin asperities is an aqueous solution composed of the fine particles contained in the cement-filler mixture. The subsequent physicochemical interactions and mechanical anchoring of the concrete to the skin [2–6] cause the formation of many aesthetic defaults such as discoloration, micro-bulling, and concrete breaking [1–3] that are visible on the surface of concrete walls after formwork removal operations. The required restoration operations are unfortunately costly and time-consuming and are unnecessary if a weak negligible skin-concrete adhesion is achievable.

The adhesion of the concrete on the skin may possibly arise from electrical bonding [4,5] and chemical bonding through the $Ca(OH)_2$ formation [4–6]. The interfacial bonding depends partly on the water-cement ratio [7], the polymer additives [5,7,8] and the filler substitutes [7]. The concrete adhesion is partially avoided by modifying the skin surface through the condensation of a water layer [9], the application of a polymer coating [4], or the spreading of release agents [10–13] prior to concrete pouring. The lubricant

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family, i.e. vegetal or mineral [11,12], the environment temperature [10] and the application mode [13] are also of major importance.

Few works have investigated the effect of the skin superficial characteristics with the concrete ability to adhere to the skin. The adhesion is avoidable with a controlled skin roughness that is low enough to avoid mechanical anchoring and high enough to avoid capillary forces [2–5] or with a controlled skin chemistry using a special galvanized superficial treatment [6]. The wear resistance to the concrete abrasion is reduced by smoothing the surface [14]. Despite these works, the topic of adhesion as it applies to skin-concrete interactions remains a contentious subject, particularly with regard to identifying the skin superficial characteristics that would ideally avoid concrete adhesion without lubricant spreading.

The present work investigates the surface characteristics of a bare and a coated mild steel formwork skins that are used on-site for their small adhesion with the concrete and good surface finish. Using the sessile drop method, the solid surface tensions were determined and correlated to the topographic and chemical signature of the skins. A scratch test procedure was specifically developed for quantifying the wear resistance of the skins. Accordingly, the experimental results of the scratch tests were implemented into different models to provide a link between the skin wear resistance and the shear stress to remove the surface layer from the steel substrate.

2. Experimental details

2.1. Materials

Mild steel samples were prepared from 5 mm-thick formwork skins that are used in the field. Skin coupons of 50 × 50 mm^2 were cut by laser at various positions on the formwork skins so as to provide a statistically significant coupon population. In addition, a commercial polymer coating used on formworks on-site was applied on several mild steel coupons for laboratory-scale characterization.

The chemical analysis of the steel skin surface was performed using scanning electron microscopy (SEM) in conjunction with X-ray diffraction (XRD). A nickel layer was deposited on the coupon surfaces to protect them from the deteriorations induced by the mechanical polishing. The coupons were immersed in the Electroless Nickel Plating Solution at a temperature between 71 °C and 82 °C with a deposition rate of 10 μm·h^{-1}. Cross sections were afterwards cut, ground, and mechanically polished using a 0.05 μm-diamond suspension. Metallic surface were observed with a scanning electron microscope (SEM) JEOL JSM-7001F using secondary electrons for the surface topography and backscattered electrons for the chemical contrast (compo mode). Micrographs of metallic samples were obtained in high vacuum (≈10^{-4} Pa) with a 15 kV-acceleration voltage at a 10 mm working distance. With the micrographic observations by SEM, energy dispersive spectroscopy (EDS) was performed using an Oxford Instruments X-max analyzer with a 20 mm^2-detection surface. EDS spectra were analyzed by means of the software INCA. Following the SEM measurements, the crystallographic phases were determined using a Siemens D500 X-ray diffractometer. A chromium anode with a Cr-Kα wavelength λ = 0.22911 nm radiation and diffraction angles 2θ from 40° to 160° at 40 kV and 30 mA were used. A vanadium filter was added in diffractometer to absorb the Cr-Kβ radiation. The pics detection was performed according to 2 θ diffraction angles through the Bragg's law.

The polymeric coating was analyzed using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and Fourier Transform-Infrared (FT-IR) Spectroscopy. TGA testing was carried out using the TA Instruments TGA Q500 thermogravimetric analyzer with a sample mass of 4.2 mg and under a 50 ml min^{-1} flow rate of nitrogen. The thermal composition was performed from room temperature to 900 °C at a heating rate of 20 °C min^{-1}. The DSC characterization was performed on a TA Instruments DSC Q10 calorimeter on 3 mg sample heated at 10 °C min^{-1} from −80 °C to 190 °C temperature range and under a 50 ml min^{-1} flow rate of nitrogen. The weight fraction crystallinity is given by:

$$X_c = \frac{\Delta H_f}{\Delta H_f^o} \quad (1)$$

where ΔH_f is the heat of fusion of the measured sample determined at endothermic melting peak and ΔH_f^o is the enthalpy of fusion of 100% crystalline material. Finally, the FT-IR analysis was realized on a Fisher FT-IR spectrometer from Perkin Elmer in transmission and ATR (Attenuated Total Reflection) modes. The sample was in contact with a diamond/ZnSe crystal. Four scans per mode were recorded over the range 4000–600 cm^{-1} with a spectral resolution of 4 cm^{-1}.

2.2. Roughness measurements

The surface topography was measured using a white-light interferometry microscope (WLIM) VEECO NT3300 over a 4 × 4 mm^2 area. The surface was sampled at 2052 × 2052 points with a 1.9 μm step scale along X- and Y-directions. 15 analyses have been carried out on 3 surfaces for each formwork skin. A multi-scale characterization of the surfaces was preliminary performed in order to determine a relevant measurement scale. Surface roughness profiles were sampled in frequency components from 3.10^{-2} to 8 mm^{-1} using the decomposition approach of continuous wavelets [15]. Above a scale of 1 mm, the surfaces showed fractal domains. Therefore, in an aim of obtaining representative data acquired in a small duration time, areas of 4 × 4 mm^2 were chosen.

The arithmetic mean height (S_a), the root mean square height (S_q), the peaks material volume (V_{mp}), the core void volume (V_{vc}) and the valley void volume (V_{vv}) were computed according to the ISO 25178 norm [16]. V_{mp}, V_{vc} and V_{vv} are calculated in three intervals: 0–10%, 10–80% and 80–100% of the bearing ratio respectively [17].

2.3. Wettability measurement

Sessile drop wettability was characterized out on the Morphoscan from Michalex Tribometrix according to the norm AFNOR EN 828 [18]. Measurements were performed without cleaning the surface so as to maintain the skin in the in-field superficial conditions. Drops were deposited in an environment of 22 ± 1 °C temperature and 54 ± 2% relative humidity. Two liquids, demineralized water and glycerol, were used with characteristics given in Table 1. A syringe of inside diameter of 4.6 mm equipped with a needle of 0.8 mm outside diameter was used to achieve the deposition of 5 ± 1 μL droplets. The capillary length K (Table 1) is given by [19]:

$$K = \sqrt{\frac{\gamma}{\rho g}} \quad (2)$$

where γ is liquid superficial tension, ρ liquid density, and g gravitational acceleration. The droplets have a radius in the 1.26 ± 0.36 mm range, smaller than the capillary length (Table 1), so that gravity is negligible. The static droplet shape on the sample's surface was recorded as a 720 × 480 pixels image ten seconds after the drop was deposited. Contact angles were measured to an accuracy of ± 2° using the open source image processing program ImageJ. Ten droplets of each liquid were deposited at different locations on the surface of each sample to obtain an arithmetic medium value of the contact angles. The contact angle was measured after the droplet spreading, meaning that the provided values are the advancing contact angles.

The analysis is founded upon the Owens-Wendt model [20] for a perfectly flat homogeneous solid surface wetted by a liquid drop:

$$\sigma_{SV} = \sigma_{LS} + \sigma_{LV}\cos\theta \quad (3)$$

where σ_{SV} and σ_{LV} are the solid–vapor and liquid–vapor superficial tensions, respectively. Eq. (3) is rewritten by implementing the polar (subscript P) and dispersed (subscript D) components of surface tensions σ_{SV} and σ_{LV} [18]:

$$\frac{(1+\cos\theta)\cdot\sigma_{LV}}{2\sqrt{\sigma_{LV}^D}} = \sqrt{\sigma_{SV}^P}\cdot\sqrt{\frac{\sigma_{LV}^P}{\sigma_{LV}^D}} + \sqrt{\sigma_{SV}^D} \quad (4)$$

where θ is the contact angle for a given liquid drop. Linear best-fitting of $\frac{(1+\cos\theta)\cdot\sigma_{LV}}{2\sqrt{\sigma_{LV}^D}}$ versus $\sqrt{\frac{\sigma_{LV}^P}{\sigma_{LV}^D}}$ estimates the polar σ_{SV}^P (slope) and dispersed σ_{SV}^D (residue) components. The surface energy of the substrate is afterward calculated as the sum of the polar σ_{SV}^P and dispersed σ_{SV}^D components.

2.4. Mechanical characterization

Hardness measurements were performed using the Morphoscan from Michalex Tribometrix equipped with a Berkovich diamond tip. The loadings were performed at a constant strain rate of 0.05 s^{-1} up to a maximum load of 150 mN for the steel skin and 5.5 mN for the polymer coating. Nanoindentations were achieved with a penetration depth smaller than 1 μm, namely less than 10% of the thickness of the top layer, to avoid the subtract influence. Load-displacement curves were processed using the Oliver and Pharr method [21,22]. Nevertheless, the absence of superficial polishing prior to nanoindentation induced a large scatter in the calculated mechanical properties.

The wear resistance of the steel skin and polymeric coating was evaluated using a Scratch Tester Millenium 200, TriboTechnic equipped with a Rockwell C diamond indenter with a 200 μm-radius hemispherical tip. The scratch test was carried out from 0 to 100 N at a loading rate of 3.3 N·s^{-1} and a scratch speed of 0.7 mm·s^{-1} along a 20 mm path. The critical normal load was determined by identifying a sudden change in the tangential and normal force behaviors. After completion of the