A comparative analysis of the wear characteristics of glazes generated on the ordinary Portland cement surface of concrete by means of CO_2 and high power diode laser radiation

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Abstract

The wear characteristics of a glaze generated on the ordinary Portland cement (OPC) surface of concrete using a 2 kW high power diode laser (HPDL) and a 3 kW CO_2 laser have been determined. Within both normal and corrosive environmental conditions, the wear rate of the CO_2 and HPDL generated glazes were consistently higher than the untreated OPC surface of concrete. Life assessment testing revealed that surface glazing of the OPC with both the CO_2 and the HPDL effected an increase in wear life of 1.3 to 17.7 times over an untreated OPC surface, depending upon the corrosive environment. The reasons for these marked improvements in the wear resistance and wear life of the CO_2 and HPDL generated glazes over the untreated OPC surface of concrete can be attributed to the partial (CO_2 laser) and full (HPDL) vitrification of the OPC surface after laser treatment which subsequently created a much more dense and consolidated surface with improved microstructure and phase characteristics which is more resistant in corrosive environments. In addition, the wear life and the wear rate of the HPDL glaze was found to be consistently higher than that of the CO_2 laser glaze. This is due to the fact that CO_2 and HPDLs have very different wavelengths; consequently, differences exist between the CO_2 and HPDL beam absorption characteristics of the OPC. Such differences give rise to different cooling rates, solidification speeds, etc and are, therefore, the cause of the distinct glaze characteristics which furnishing each microstructure with its own unique wear resistance characteristics.

Keywords: High power diode laser (HPDL); CO_2 laser; Ordinary Portland cement; Surface glazing; Wear; Life characteristics

1. Introduction

Material conservation is becoming a matter of increasing importance in the present and foreseeable world economy. Wear is a major cause of concrete wastage in many application areas where over time and as a direct consequence of the operating environment, the concrete becomes corroded and/or contaminated. This ultimately necessitates the arduous and costly undertaking of repairing or replacing the affected concrete either by physical or mechanical means. Clearly, any means by which the life of the concrete could be extended would be of great interest to all engineers, since any reduction in concrete wear could yield significant economic savings.

The relatively recent emergence of the technology of laser materials processing offers a viable alternative to the existing methods for improving the wear characteristics of concrete. Owing to their unique characteristics, lasers have the propensity to be employed for the non-contact processing of materials, such as concrete, which are otherwise difficult to process. To date, inroads have been made in establishing the laser processing of concrete. Most of the research, however, has concentrated on the laser cutting of concrete and reinforced concrete using high power CO_2 lasers, most prominently with regard to nuclear reactor decommissioning [1-3]. Also, as part of nuclear plant decommissioning, Li et al. [4-7] conducted research to determine the workability of several laser techniques for sealing/fixing radioactive contamination onto concrete surfaces. Such techniques experimented with were: direct glazing of the concrete, single and multiple layer fusion cladding and combined chemical/fusion cladding. Work by Sugimoto et al. [8] focused upon modifying the surface appearance and surface properties of cement based materials using a high power CO_2 laser. The laser treatment produced novel surfaces, with surface textures, properties and appearance unique to laser treatment. The resultant physical characteristics and mechanical behaviour of the post-process cement based materials was later fully characterised by Wignarajah et al. [9]. Borodina et al. [10] has carried out investigations into the structural changes within the composition of zirconia concrete caused by surface exposure to CO_2 laser radiation, detailing microstructural changes, phase changes and the absorptivity characteristics. In all of these studies, spallation and excessive cracking and porosity formation were found to be major problems undermining the performance of the laser treated surface layer.

In contrast, more detailed and comprehensive studies conducted by Lawrence and Li have investigated the feasibility and characteristics of high power diode laser (HPDL) generated glazes on the ordinary Portland cement (OPC) surface of concrete [11, 12]. In further work, Lawrence and Li studied the generation and carried out a comparison of the glazes generated with both CO_2 and HPDL's [13, 14].

This present work is concerned with determining the wear characteristics of a glaze generated on the OPC surface layer of concrete by means of CO_2 and HPDL irradiation, and investing the differences thereof. This is of particular interest since both lasers have very different operating characteristics and my therefore yield very different results. In any case, it is hoped that this work will demonstrate the practicability and efficacy of employing lasers for the processing of not only concrete, but many other building materials.

2. Experimental procedures

2.1 Materials

The concrete studied in the experiments was the ubiquitous OPC based concrete, with the usual 'as cast' OPC surface of concrete being the subject of the HPDL irradiation. The OPC surface of the concrete had a thickness of 2.5 mm. For the purpose of experimental convenience the as-received concrete blocks were sectioned into squares (120 x 120 x 20 mm^3) prior to laser treatment. The composition of the concrete bulk by volume is as follows: 20mm limestone aggregate (40%), 10mm limestone aggregate (14%), zone M sand (28.5%), OPC (10.5%) and particulate fine aggregate (7%).

2.2 Laser processing procedure

This work was conducted using a CO_2 laser (Trumpf, GmbH.) and a GaAlAs HPDL (Rofin-Sinar, GmbH., DL 020 S). The CO_2 laser emitted at a wavelength of 10.6 μm and produced a multimode beam with a maximum output power of 3 kW. The CO_2 laser was integrated into a 5 axis computerised numerical control (CNC) workstation and so a series of optical units were used to deliver the beam through a 2-axis (linear) and 2-axis (rotary) laser head to the concrete workpieces. The beam was focused onto a plane above the surface of the OPC surface of the concrete using a 200 mm focal length KC1 lens to give a stable diverging beam. The HPDL used in this work emitted a

high order mode beam at 808 ±10 nm with a maximum output power of 2 kW. The HPDL beam was delivered to the concrete workpieces by means of an optical fibre 10 m long and of 1500 μm core diameter. The end of the fibre was connected to a focusing lens assembly with a focal length of 42 mm and was mounted on the z-axis of a 3-axis CNC gantry table. The OPC surface of the concrete samples was irradiated with the HPDL beam by traversing the samples beneath the beam using the x- and y-axis of the CNC gantry table. Both lasers were operated in the continuous wave (CW) mode and in both processes, the fumes produced were removed with an extraction system, whilst an O_2 process gas being coaxially blown at a rate of 3 l/min was used to shield the laser optics and assist in the laser processing of the OPC surface of the concrete. The OPC surface of the concrete samples were irradiated with both lasers using laser power densities of 2.25 kW/cm^2 with traverse speeds of 240 mm/min and laser spot diameters of 10 mm. Only single tracks were generated with no overlapping.

2.3 Wear testing procedure

To determine the wear resistance characteristics of the CO_2 and HPDL generated glazes on the OPC surface of concrete, as well as those of an untreated OPC surface, wear tests were conducted in accordance with Fig. 1. For experimental purposes the concrete samples were cut into smaller pieces (25 mm x 25 mm). Half of the samples were then laser treated. All the samples were then weighed. The samples were then clamped individually in the vice of a common shaping machine. To provide abrasion and consequently cause wear on the surface of the samples, a spherical steel slider was attached to the floating head of the shaping machine and moved cyclically back and forth across the untreated and laser treated glazes on the OPC surfaces. The spherical steel slider was fabricated from a 25.4 mm diameter ball bearing with a hardness value of 700 VHN. As one can see from Fig. 1, the spherical steel slider was blunt and made a single point contact with the surfaces of the samples. The total distance moved in one cycle was 6 mm while the traverse speed was 180 mm/min. By applying weights to the floating head a frictional force of 60 N was generated. The samples were subjected to the frictional force for 8 h, being removed from the machine and weighed at 2 hourly intervals. The wear testing of the laser treated samples was carried out on single laser tracks of 10 mm width with no overlapping. Following completion of the wear tests it was observed that both of the laser generated glazes were present.

3. Results

3.1 Wear characteristics in normal environmental conditions

In most cases the wear resistance of a material is related to the hardness of the material in comparison with the that of other materials with which it subsequently comes into contact with [15]. However, wear resistance is not directly proportional to hardness, nor does it always increase with hardness [16]. Fig. 2 shows the relationship between weight loss and the friction time for the laser generated glazes on the OPC and the untreated OPC. As one can see, the wear resistance of the HPDL generated OPC glaze is fractionally greater than that of the CO_2 laser generated OPC glaze. However, both the OPC laser glazes displayed a significant increase in wear resistance over the untreated OPC surface, with the weight loss being approximately 2 times lower after 4 h, and 3 times lower after 8 h.

3.2 Wear characteristics in corrosive environments

Concrete surfaces are often subjected to corrosive substances, either as part of the normal service environment and/or as a result of routine cleaning. Therefore, corrosion resistance tests based upon BS 6431 [17] were conducted using nitric acid, sodium hydroxide and a detergent cleaner. The experiments were carried out by dropping small amounts of the corrosive agents on to the surface of the CO_2 and HPDL glazed OPC surfaces, as well as the untreated OPC surface of the concrete, at hourly intervals for four hours. The reagents were applied in the concentration ratios of 80%, 60%, 40%, 20% and 10%. The samples were then examined optically, as well as being mechanically tested in terms of compressive strength and wear. High concentrations of the various corrosive agents were used principally to accelerate the tests. However, in practice 60% nitric acid is used within the nuclear processing industry as a solvent for nuclear fuels [18].

All three substances in the concentrations 80%, 60% and 40% were seen to immediately attack the untreated OPC surface, with the nitric acid and sodium hydroxide attacking with greater severity than the detergent. On the other hand, both the CO_2 and HPDL glazed surfaces displayed no discernible microstructural changes or signs of devitrification due to corrosion.

Tests conducted according to ASTM C579-91 [19] revealed that exposure of the untreated OPC surface to the reagents had a significant effect on the compressive strength and the wear resistance of the OPC. As Fig. 3 shows, exposure of the OPC to nitric acid and sodium hydroxide in the concentrations 40-80% resulted in an average loss of compressive strength of approximately 19-37%.

In the case of the detergent a discernible loss in compressive strength only occurred with concentrations above 40%. Here the average loss in compressive strength for concentrations in the range 60-80% was approximately 17%. This compares with no discernible difference in either the wear resistance or the compressive strength of the laser glazed OPC surfaces. Similarly, as Fig. 4 shows, the wear resistance of the untreated OPC surface when exposed to the reagents with an 80% concentration was significantly affected, particularly through interaction with the nitric acid and the sodium hydroxide. Here the weight loss was approximately 5 times higher than for the unexposed OPC after 4 h, and approximately 11 times higher after 8 h for the nitric acid. In the case of the detergent the weight loss was marginal after both 4 and 8 h.

4. Discussion

It is evident from the results of the wear tests that the CO_2 and HPDL generated OPC glazes out performed the untreated OPC surface. This was especially true in the case of wear tests conducted in corrosive environments, where both of the OPC laser glazes proved to be resistant to the corrosive elements for the duration of the experiments. This marked variation in corrosion resistance can be ascribed to the difference in structure of the laser generated OPC glazes and the untreated OPC.

Although the chemistry of the OPC surface of concrete and the hydration of its various constituents is has not yet been fully resolved due to its complex nature, it is known that the constituents of OPC are minerals which exist as multi-component solid solution chemical compounds. One of the major constituents of OPC is Ca, however, of particular importance with regards this study, OPC contains in relatively large proportions: SiO_2 (21wt%); Al_2O_3 (5wt%) and Fe_2O_3 (3wt%), which are basic glass network formers and modifiers. Consequently the intense local heating brought about by the incident CO_2 and HPDL beams results in the melting of these compounds at around 1283^0C, thereby causing the materials to lose the retained water and form an amorphous glassy material consisting of various calcium-silicate-alumina compounds [20]. Indeed, whereas the HPDL generated OPC glaze is of a fully amorphous nature and the CO_2 laser OPC glaze is of a semi-amorphous nature, the untreated OPC is comprised of a porous polycrystalline structure (see Fig 5); thus the untreated OPC is readily attacked by acids, whilst the amorphous structures of both OPC laser glazes ensures an increase in corrosion resistance [12]. Indeed, this postulation is borne out somewhat when one considers the laser generated microstructures. In Fig. 6(a) the microstructure of the HPDL generated glaze can be seen to

have no discernible structure and appears to be fully amorphous. But, even though sizeable areas of the CO_2 laser generated OPC glaze exhibit a randomly located regular columnar structure, the majority of the CO_2 laser generated OPC glaze appears to be of an amorphous structure and thus affords the glaze adequate protection against corrosive reagents.

It is within this glazed region that the reasons for the differences in the performance of OPC glaze generated with the CO_2 and the HPDL exists. As is evident from Fig. 7, cracking and the formation of pores in the CO_2 and HPDL induced glazes occurred to various degrees depending upon the laser used. The formation of cracks can be attributed mainly to thermal stresses generated during laser irradiation. This is due to the fact that OPC has low thermal conductivity, and, as such, during laser heating a large thermal gradient between the melt zone and the substrate exists which results in the generation of thermal stresses. Additionally, despite the fact that the laser surface treatment process is effectively localised in nature, the fact remains that a certain amount of the heat generated will be conducted to sections of the OPC where the surface is already glazed. This, combined with existence of a relatively cold OPC substrate means that thermal stresses will be generated. During the heating phase the stresses will be compressive and relieved by plastic deformation, thus precluding crack formation. At high temperatures ($T \geq T_m$) the stresses can also be relieved [21-23]. However, during cooling when the temperature falls below T_m, then stresses will accumulate. If the fracture strength of the material is exceeded, then cracking within the melted layer will occur. The thermal stress σ, induced by a thermal gradient can be calculated using the Kingery equation:

$$\sigma = \frac{E \alpha \Delta T}{1 - \upsilon} \qquad (1)$$

where E is Young's modulus, ΔT is the temperature change, α is the coefficient of thermal expansion and υ is Poisson's ratio. If it is assumed that the glass formed on the surface of the OPC is similar to soda-lime-silica glass because the compositions of the two materials are similar, then the following values for a typical soda-lime-silica glass can be used: E=6.42 x 10^4 MN m^{-2}, α=33 x 10^{-7} K^{-1} and υ=0.176. So, when the OPC surface of the concrete was irradiated by the CO_2 laser beam ΔT=1390^{0}C and for the HPDL ΔT=1263^{0}C, then by substituting the values into Equation (1) the CO_2 and HPDL beams produced a thermal stress in the resulting glass of around 305 and 254 MN/m^2 respectively. Since this is well in excess of the fracture strength of the glass (glaze), 120 MN/m^2 [24], cracking will occur, and can only be avoided by severe distortion or through the reduction of ΔT by pre-heating.

From Fig. 7 it can be seen that the pores formed in the CO_2 and HPDL induced glazes varied in size from microscopic pits to large craters depending upon both the laser operating parameters and the actual laser employed. For all instances of pore formation the mechanism behind their development is the consequence of gas escaping from within the melt and disrupting the surface [25]. With regard to the OPC glaze, the gas is likely to be CO_2 [9]. If the laser energy density incident on the OPC is too low, then the generated CO_2 can not escape from the molten OPC surface easily because of the high viscosity of the melt. As such, when the CO_2 gas eventually does penetrate the melt surface, the resultant pore is not filled by the flow of the melt; since the insufficient energy density is unable to maintain a high enough temperature for an adequate length of time and thus decrease the overall viscosity of the melt [26]. In this case the pores formed are typically small and shallow, being regular in both periodicity and intensity . On the other hand, if the laser energy density incident on the OPC surface of the concrete is too high, then boiling of the surface may happen. At the same time an increase in CO_2 gas formation may occur within the melt. These individual pockets of CO_2 gas formation may combine and rise to surface of the melt. Once the energy density decreases (as the laser traverses away), then the additional CO_2 gas will attempt to escape from the molten surface. However, the solidifying melt will prevent this, causing bubbles to form. The excessive CO_2 gas pressure will firstly cause the bubbles to expand and ultimately rupture the walls of the bubbles creating a sharp 'knife edge' pore [4, 9]. These types of pore are usually large, deep and randomly spaced.

The pores and cracks generated following laser treatment, especially CO_2 laser treatment, will play a vital role in determining the wear characteristics of the glazes due to their influence on the surface roughness. The average surface roughness (Ra) of the untreated OPC surface was 21.91 μm, whilst for the CO_2 and HPDL generated glazes the surface roughness was measured as 5.04 μm and 2.88 μm respectively. Such differences in the surface roughness values of the laser generated glazes can be attributed to the differences in wavelength, and in turn absorption characteristics differences which cause different cooling and solidification rates. It is worth remarking that, perhaps unsurprisingly, the surface roughness measurements show some correlation with the wear test results given in Fig. 2.

The generally superior mechanical and chemical performance of the laser generated OPC glazes over the untreated OPC suggests that the life characteristics of the OPC glazes may also be superior to those of untreated OPC. Yet in any analysis of the wear life of the two materials, the in-situ relative thickness of the HPDL generated glaze and the untreated OPC layer on concrete must be considered

in order to give a true interpretation of the actual life characteristics. This is particularly true when considering the wear resistance (with and without exposure to corrosive chemical agents). Consequently the increase in wear life can be given by

$$\text{Increase in wear life} = \frac{\text{Laser glaze wear life}}{\text{Untreated OPC wear life}} \qquad (2)$$

where, $$\text{Wear life} = \frac{\text{Density . Thickness (mg/cm}^3/\text{cm)}}{\text{Wear rate (mg/cm}^2/\text{h}^1)} \qquad (2a)$$

Table 1 summarises the wear rate details and the nominal life increase of the HPDL generated glaze over the untreated OPC surface. As is clearly evident from Table 1, the HPDL generated glaze effected an increase in actual life over the untreated OPC surface regardless of the environment. Further, it can be seen that the increase in actual life of the HPDL generated glaze over the untreated OPC surface varies considerably depending upon the working environment. Notwithstanding this, arguably the most common working environment for an OPC surface would involve some contact with at least detergent acids, therefore yielding significant economic savings since a HPDL glazed OPC surface lasts around 2.5-times longer than one which is unglazed.

5. Conclusions

The wear characteristics of a glaze generated on the ordinary Portland cement (OPC) surface of concrete was using a 2 kW high power diode laser (HPDL) and a 3 kW CO_2 laser have been determined. Within both normal and corrosive (detergent, NaOH and HNO_3) environmental conditions, the wear rate of the CO_2 and HPDL generated glazes were 3.9 mg/cm^2/h and 3.5 mg/cm^2/h respectively. In contrast, the untreated OPC surface of concrete exhibited a wear rate of 9.8 mg/cm^2/h in normal environmental conditions and 18.5, 73.8 and 114.8 mg/cm^2/h when exposed to detergent, NaOH and HNO_3 respectively. Life assessment testing revealed that surface glazing of the OPC with both the CO_2 and the HPDL effected an increase in wear life of 1.3 to 17.7 times over an untreated OPC surface, depending upon the corrosive environment. The reasons for these marked improvements in the wear resistance and wear life of the CO_2 and HPDL generated glazes over the untreated OPC surface of concrete can be attributed to: (i) the partial (CO_2 laser) and full (HPDL) vitrification of the OPC surface after laser treatment which subsequently created a much more dense and consolidated surface that is effectively a glass and (ii) the generation of a surface with improved

microstructure and phase which is more resistant in corrosive environments. The wear life and the wear rate of the HPDL glaze was consistently higher than that of the CO_2 laser glaze. This is due to the fact that the wavelengths at which both lasers emit at are very different and consequently, differences will exist between the CO_2 and HPDL beam absorption characteristics of the OPC. Such differences are the cause of the distinct glaze characteristics, with the glaze generated after HPDL interaction being fully amorphous in nature, whilst the glaze generated after CO_2 laser interaction was seen to be of a semi-amorphous structure, with sizeable areas of a regular columnar structure randomly located within the glaze. In turn, each microstructure will possess its own unique wear resistance characteristics.

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Fig. 1. Schematic illustration of the experimental set-up for the wear tests.

Fig. 2. Relationship between weight loss and friction time for the treated (CO_2 and the HPDL) and untreated OPC surface of concrete.

Fig. 3. Variation in compressive strength of the untreated OPC with reagent type and reagent concentration.

Fig. 4. Relationship between weight loss and friction time for the untreated OPC surface with different reagent types at the maximum concentration (80%).

Fig. 5. XRD analysis of the OPC surface (a) before laser treatment, (b) after CO_2 laser treatment and (c) after HPDL treatment.

Fig. 6. Typical SEM micrograph of the fracture section of the OPC surface glaze generated with (a) the HPDL and (b) the CO_2 laser.

Fig. 7. Typical optical surface morphology of the OPC surface glaze generated with (a) the CO_2 laser and (b) the HPDL.

Fig. 1.

CO$_2$/HPDL/Untreated OPC surface

Concrete

F = 60 N

Floating machine head

Spherical steel slider

Vice
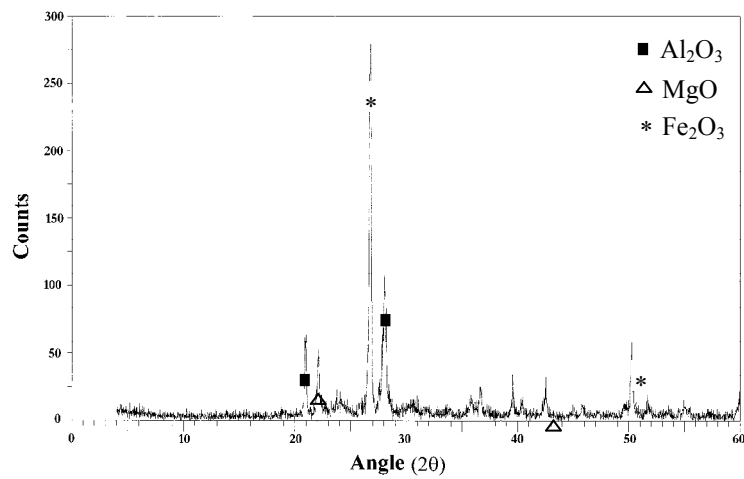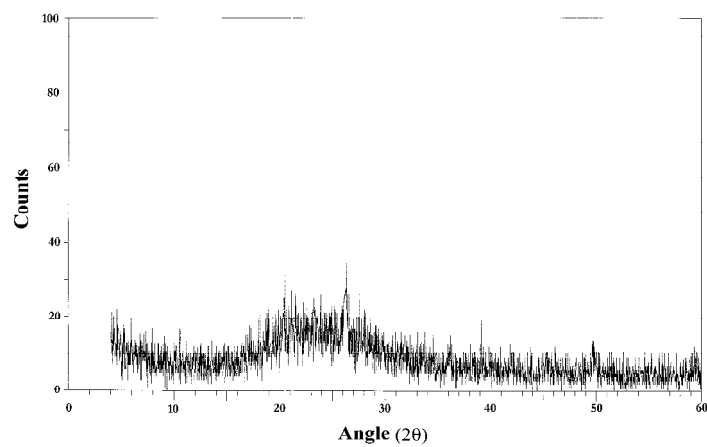
Machine bed

6mm

180 mm/min
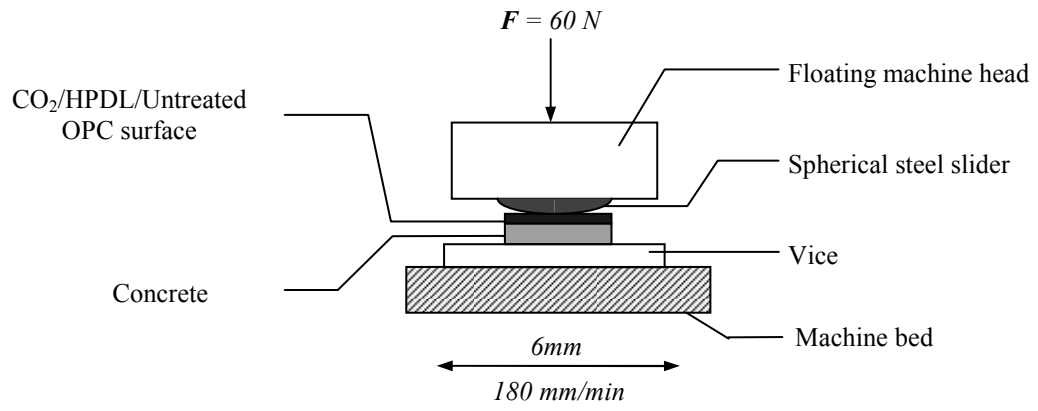
Fig. 2
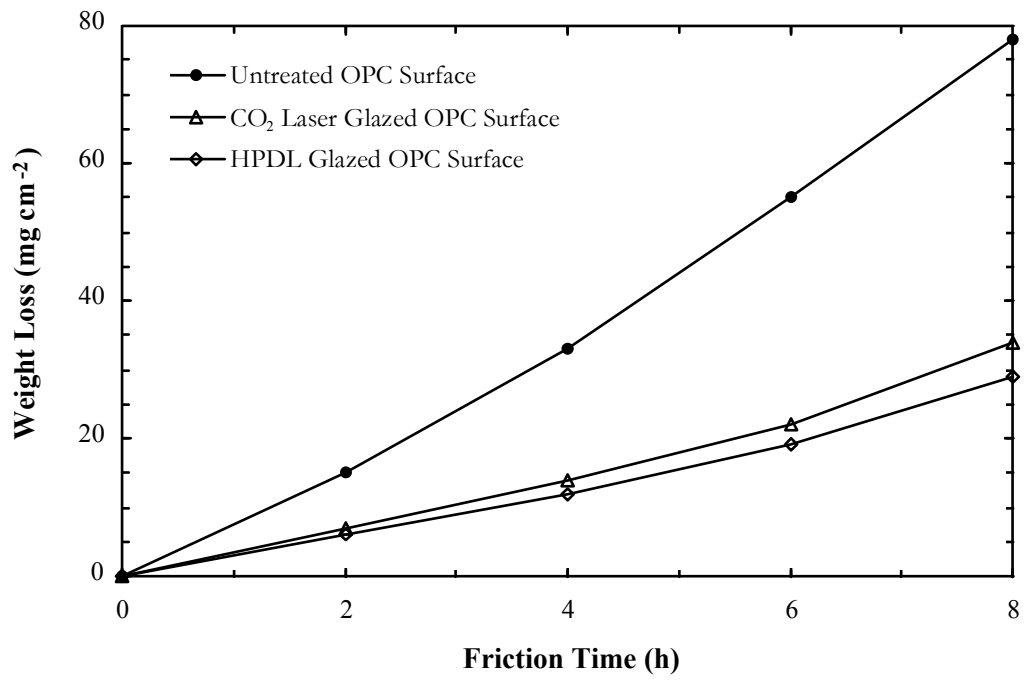
Fig. 3
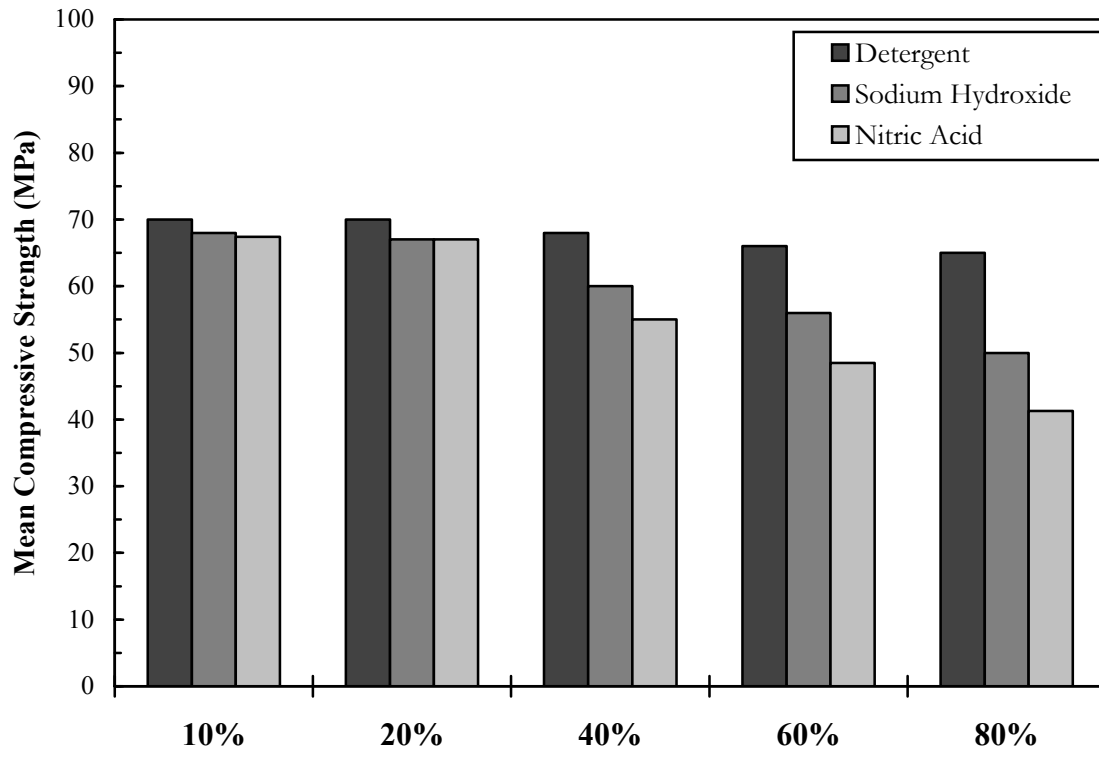
Fig. 4

Fig. 5

(a)

(b)

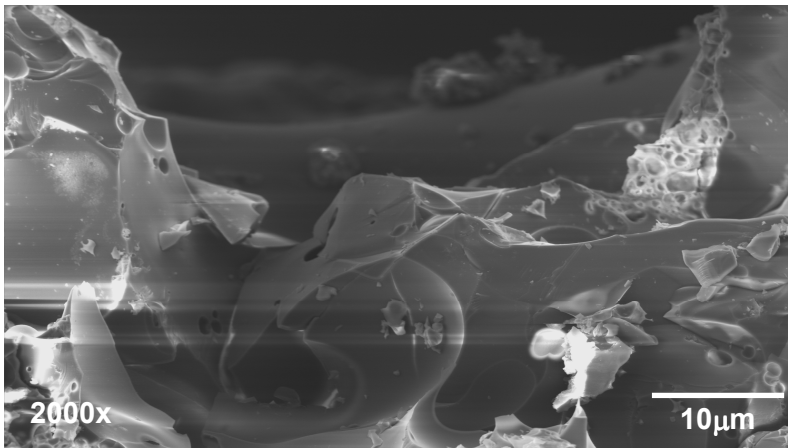
(c)

Fig 6

(b)

(a)

Fig. 7

Porosity

Crack

1mm

(a)

Porosity

Cracks

1mm
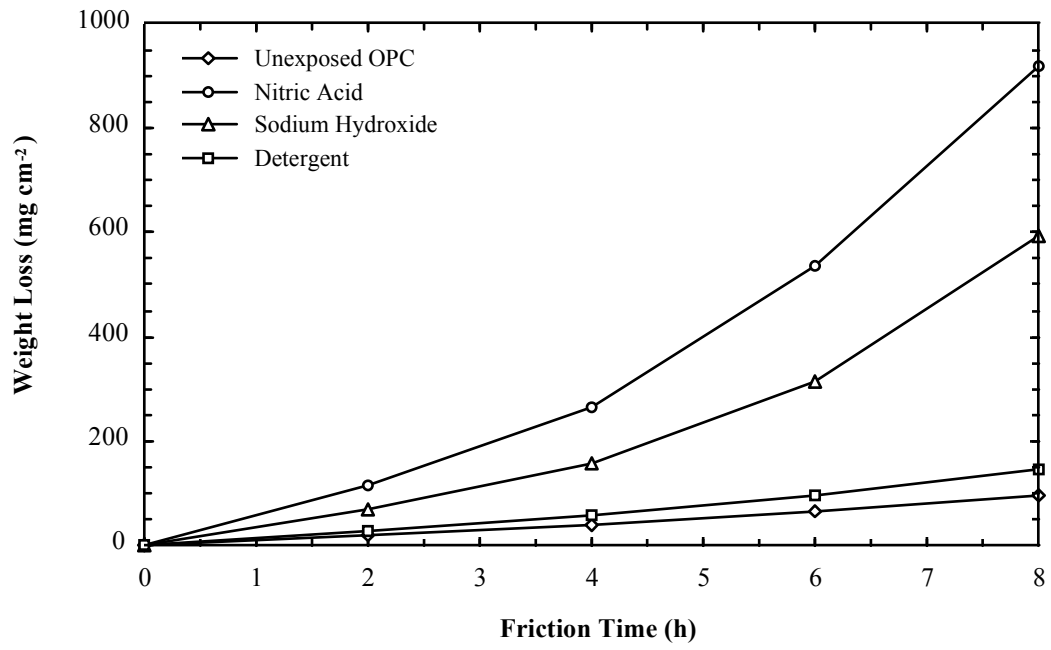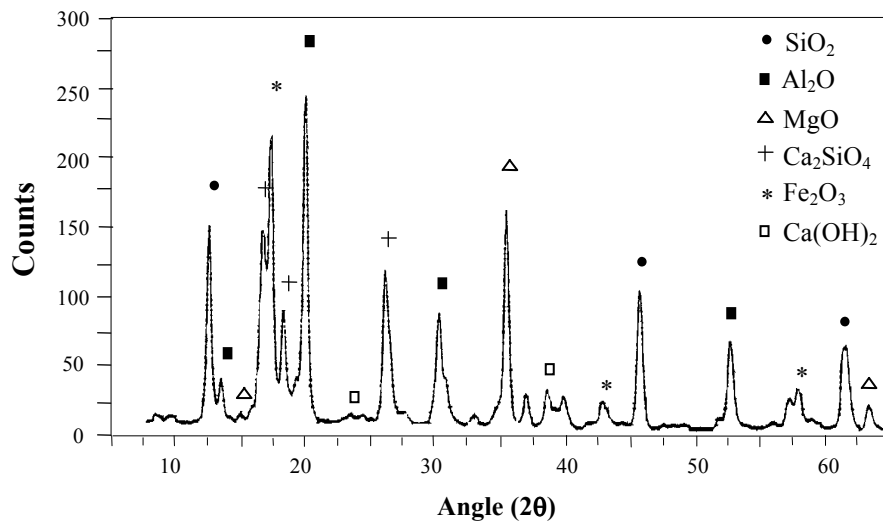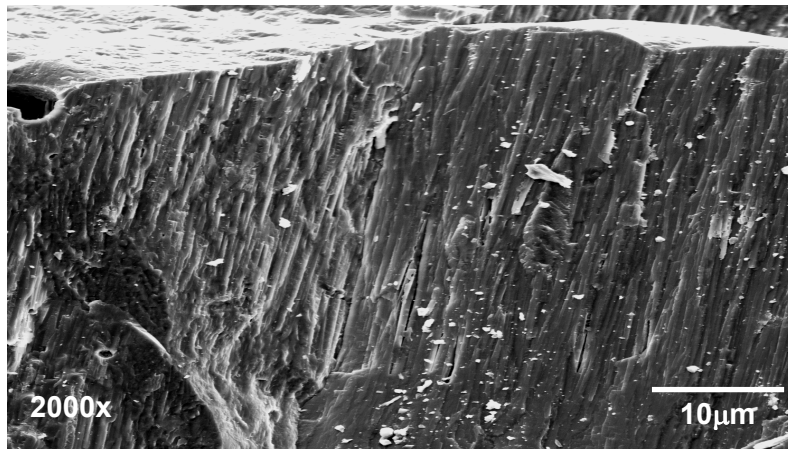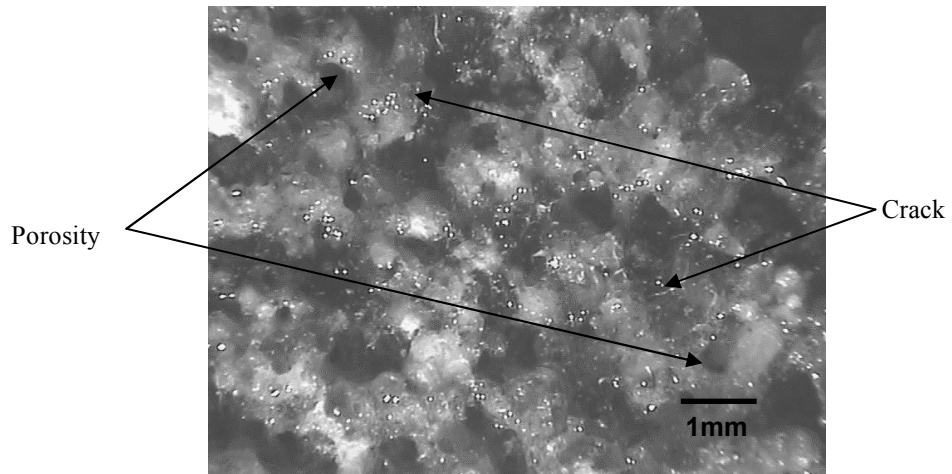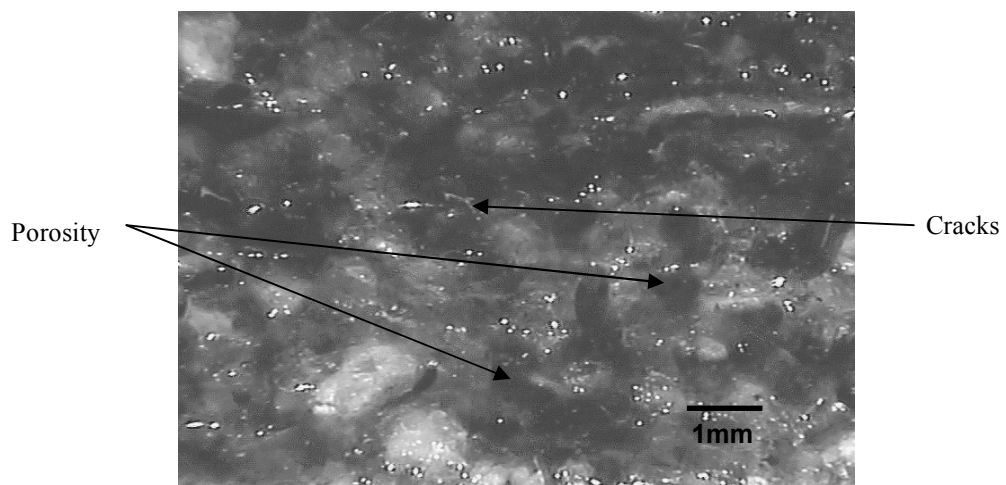
(b)

List of tables

Table 1. Wear rate details and the nominal life increase of the OPC laser glaze over untreated OPC in various corrosive environments.

Table 1.

	Density	Thickness	Wear Rate (mg cm^{-2} h^{-1})			
			Unexposed	Detergent	NaOH	HNO$_3$
Untreated OPC	2220 (kg m^{-3})	1500 (μm)	9.8	18.5	73.8	114.8
CO$_2$ laser generated OPC glaze	2000 (kg m^{-3})	1000 (μm)	3.9	3.9	3.9	3.9
HPDL generated OPC glaze	2000 (kg m^{-3})	750 (μm)	3.5	3.5	3.5	3.5
Increase in Wear Life (CO$_2$)	~	~	**1.5**	**2.8**	**11.4**	**17.7**
Increase in Wear Life (HPDL)	~	~	**1.3**	**2.4**	**9.5**	**14.8**